C

Observed Climate Variability and Change

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CONTENTS

EXECUTIVE SUMMARY

1. Globally-averaged land and ocean surface temperatures for 1990 and 1991 have been similar to those of the warmest years of the 1980s and continue to be warm relative to the rest of the record. Trends show, however, regional and seasonal diversity and not every region shows warming.

2. Continuing research into the nineteenth century ocean temperature record has not significantly altered our calculation of surface temperature warming of 0.45±0.15°C since the late nineteenth century.

3. In those land areas for which we have adequate data on maximum and minimum temperatures (approximately 25% of the global land mass), the observed warming over the past several decades is primarily due to an increase of the daily minimum (night-time) temperatures with little contribution from the daily maximum (daytime) temperatures. The source of the greater warming at night relative to that by day is not clear but could be related to enhanced cloudiness, increasing concentrations of man-made sulphur-based aerosols, increasing concentrations of greenhouse gases and possibly to residual urbanization effects in the record.

4. A new analysis of radiosonde data confirms that mid-tropospheric warming has occurred over the past several decades. Combining information from the two available analyses, the radiosonde data show a mid-tropospheric warming at the rate of 0.21°C/decade in the Northern Hemisphere and 0.23°C/decade in the Southern Hemisphere over the period 1964-1991. By contrast, the new analysis of upper tropospheric temperature changes shows less cooling than estimated in the 1990 Scientific Assessment. However, time-varying biases known to exist in radiosonde temperature instruments have yet to be quantified.

5. Microwave Sounding Unit (MSU) data provide a more complete satellite-based global dataset for tropospheric and stratospheric mean temperatures, but the record is still too short for a meaningful assessment of trends. MSU data show less warming in the mid-troposphere than do the radiosonde data since 1979, though a full analysis of inhomogeneities in the MSU data that might affect trends has not been done. Because of volcanic eruptions, the MSU data show substantial 1-2 year time-scale stratospheric (100-50 hPa) warmings exceeding 1°C on a global average. However, after combining information from the two available analyses, the longer global radiosonde record shows a lower stratospheric cooling at the rate of -0.45°C/decade over the period 1964-1991.

6. The recent eruption of Mount Pinatubo injected two to three times as much sulphur dioxide (SO_2) into the stratosphere as did the El Chichon eruption. The tropical stratosphere warmed by several degrees in response but is now cooling again. A global surface and tropospheric cooling of several tenths of a degree is possible over the next year or two due to this eruption, the amount depending on the counterbalancing warming influence of the current El Niño event in the tropical Pacific and other natural influences. However, if any cooling occurs, it will be short-lived compared with time-scales of greenhouse-gas-induced climate change.

7. Precipitation variations of practical significance have been documented in a number of regions on many time and space scales. Owing to data coverage and inhomogeneity problems, however, we cannot yet say anything new about global-scale changes.

8. Evidence continues to support an increase in water vapour in the tropical lower troposphere since the mid-1970s, though the magnitude is uncertain due to data deficiencies. An increase is consistent with the observed increase in lower tropospheric temperature. However, we cannot say whether the changes are larger than natural variability.

9. Northern Hemisphere snow cover continues its tendency to be less extensive than that observed during the 1970s when reliable satellite observations began. Its reduction relates well to simultaneous increases of extratropical Northern Hemisphere land air temperature.

10. No systematic change can be identified in global or hemispheric sea-ice cover since 1973 when satellite measurements began.

11. Some influence of solar changes on climate on the time-scale of several sunspot cycles is plausible but remains unproven.

12. It is still not possible to attribute with high confidence all, or even a large part of, the observed global warming to the enhanced greenhouse effect. On the other hand, it is not possible to refute

the claim that greenhouse-gas-induced climate change **has** contributed substantially to the observed warming. The findings that increasing concentrations of man-made tropospheric aerosols have tended to cool the climate and that decreased lower stratospheric ozone is also likely to have a cooling effect in the troposphere, help to bring the observed warming into better accord with model estimates of the warming effect of increasing greenhouse gases.

C1 Introduction

We present a supplement to Section 7 (Folland *et al.*, 1990b - hereafter referred to as S7) "Observed Climate Variations and Change" of the 1990 IPCC Scientific Assessment (IPCC, 1990). It should be read in conjunction with S7 to obtain a fuller discussion of observed climate variations and changes. The main purpose of the supplement is to introduce new findings and to update important time-series and maps contained in S7 with emphasis on large spatial scales and recent satellite evidence. Consistent with this approach, most of the references contained in Section C are confined to those published since 1989 or to those which are in press. Some work on the detection and attribution of climate change is also briefly reported, a subject previously contained in Section 8 (S8) of the Scientific Assessment "Detection of the Greenhouse Effect in the Observations" (Wigley and Barnett, 1990). Although mainly discussed in Section A of the present report, we also mention recent findings relevant to interpretation of the climate record in terms of "external" forcing factors like solar variations and tropospheric and volcanic aerosols. Discussion of the surface cooling effect of recent lower stratospheric ozone reductions is confined to Section A, as there is no unambiguous observational data available to confirm this.

C2 Palaeoclimate Variations and Change - Climates Mainly Before the Late Nineteenth Century

Several recent palaeoclimate studies are mentioned here for their probable importance in estimating natural low-frequency climate variability. Note that each series is limited to sampling a small area and most of the series are biased towards measuring one or two seasons. (When interpreting this Section, the reader may wish to refer forward to the discussion of the instrumental temperature record in Section C3.1).

A study of one thousand years of tree-ring data (Cook *et al.*, 1991) confirms a strong twentieth century warming of summer temperature in Tasmania following a pronounced cold period in the early 1900s, though the warming is still within the range of natural climate variability experienced over the past 1000 years. The strong twentieth century warming is consistent with New Zealand tree ring evidence (Norton *et al.*, 1989) and large glacial retreats there since 1860 (Salinger, 1990). However, no allowance has been made in these and similar studies for the possible fertilization effect of twentieth century increases in carbon dioxide (CO_2) on tree growth, neglect of which might lead to an overestimate of recent warming.

Oxygen isotope measurements from the northern Antarctic Peninsula have been interpreted as evidence of ***warmer*** temperatures during the nineteenth century compared with the twentieth century (Aristarain *et al.*, 1990). However, the isotope/temperature link is weak both physically and statistically (Peel, 1992), and accumulation rate changes, which are more directly related to *in situ* temperatures, point to ***cooler*** conditions in the nineteenth century (Jones *et al.*, 1992). Fragmentary evidence from expedition reports also points to cooler conditions during the first decade of the twentieth century (Jones, 1990).

A recent study of documentary evidence in China (Wang and Wang, 1991; Wang *et al.*, 1991) reveals that the seventeenth and nineteenth centuries were the coldest periods there in the last 500 years (Figure C1a and 1b). Finally, Briffa *et al.* (1992) have expanded the analysis presented in an earlier paper (Briffa *et al.*, 1990) where they use tree-ring data to reconstruct summer temperatures for northern Fennoscandia since AD 500. Their new analysis is designed to highlight greater than century time-scale variability which was largely removed by the analysis procedure they used previously. They find good evidence **in this region** for a "Medieval Climatic Optimum" (S7, p 202) around 870-1110, another warm period around 1360-1570, and a "Little Ice Age" (S7, p202) period around 1570-1750. Because of the pronounced multidecadal temperature fluctuations in their data, Briffa *et al.* (1990) suggest that greenhouse-gas-induced summer warming in Fennoscandia might not be detectable until after AD 2030.

A considerable number of instrumental records, mainly but not exclusively in Europe, extend back prior to the late nineteenth century, such as the De Bilt temperature record in the Netherlands, to 1706 (van Engelen and Nellestijn, 1992) and the Central England temperature record in England, to the late seventeenth century with homogenized daily values back to 1772 (Parker *et al.*, 1992). Such records could be combined with palaeoclimate data to

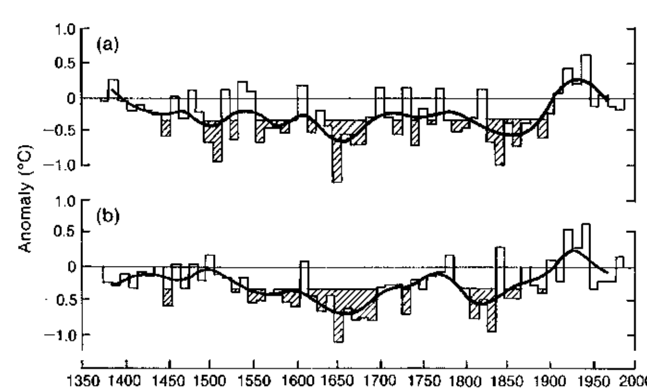


Figure C1: (a) Variations ("anomalies") of air temperature in East China (approximately 25°-35°N, 110°-122°E) since 1380, relative to 1880-1979, based on documentary evidence. The smoothed curve is a 50-year running average. Decades colder than the 1380-1879 average are shaded. (b) As (a) but for North China (35°-45°N, 110°-120°E). From Wang and Wang (1991).

provide a more detailed history of climate back to the eighteenth century (Bradley *et al.*, 1991). Thus, Lough (1991) has combined observed rainfall and river flow data with data on coastal coral growth to provide a proxy summer rainfall record for Queensland back to 1735.

C3 The Modern Instrumental Record

C3.1 Surface Temperature Variations and Change

C3.1.1 Hemispheric and Global Land Temperature

There are three independently derived, but overlapping data sets, those of Hansen and Lebedeff (1988), Jones (1988) and Vinnikov *et al.* (1990). These show noticeable differences (Elsner and Tsonis, 1991a), attributed to differences in the amounts of raw data (especially in the early parts of the record, for which the Jones data set is more comprehensive than the other two), from the methods used to ensure homogeneity of individual station records, and from methods used for spatial averaging. Jones *et al.* (1991) discuss differences between the data sets in detail. Nonetheless, the average intercorrelation between the global annual temperature anomalies from all three sets between 1881 and 1990 is 0.94.

The Jones hemispheric land air temperature series are

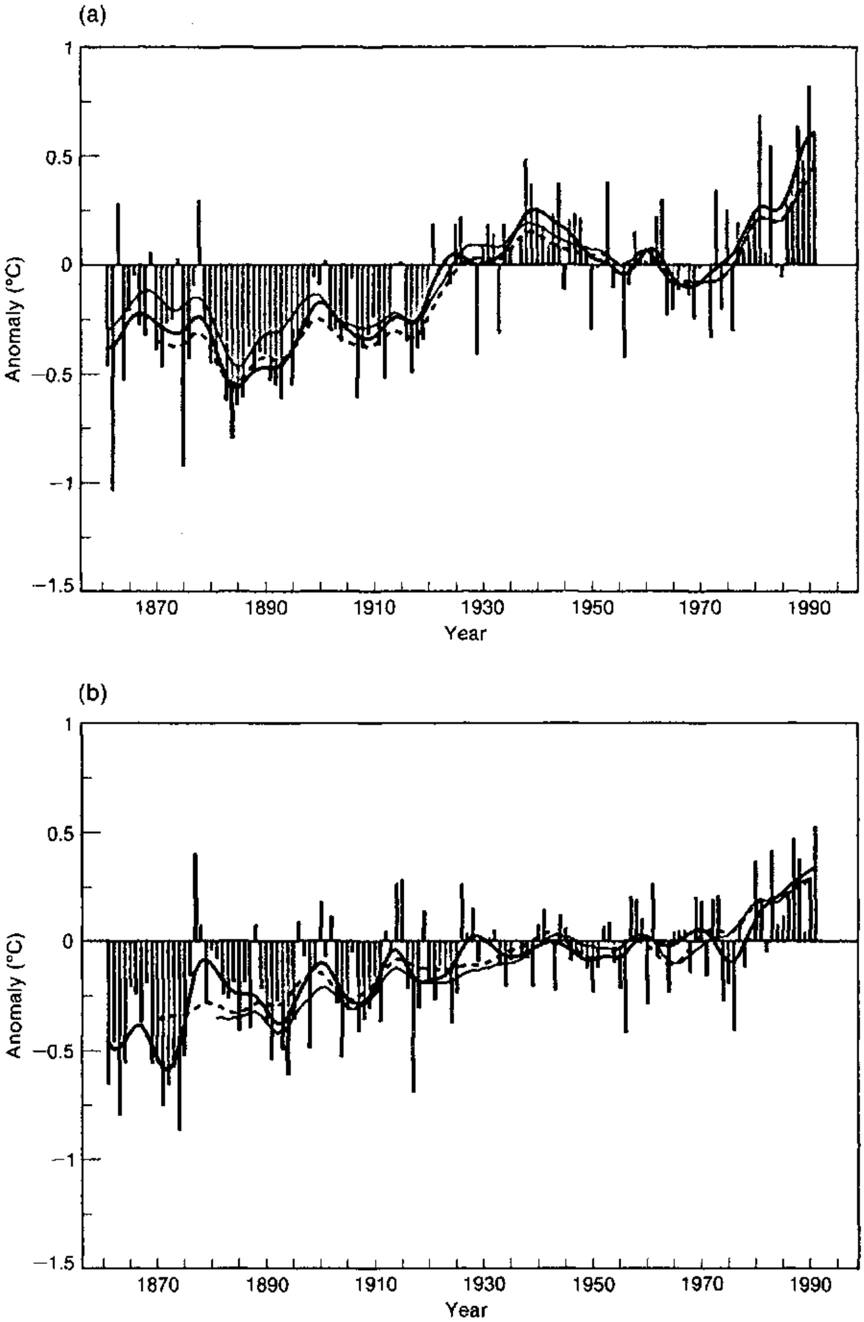


Figure C2: Land air temperature anomalies, relative to 1951-1980. Annual values from Jones (1988, updated). Smoothed curves: thick solid line = Jones (1988, updated) (1861-1991); dashed line = Hansen and Lebedeff (1988, updated) (1870-1991); thin solid line = Vinnikov *et al.* (1990, updated) (1861-1990 NH and 1881-1990 SH). (a) Northern Hemisphere; (b) Southern Hemisphere.

extended to 1991 in Figures C2a and 2b (vertical bars show annual Jones data) and the smoothed Hansen and Lebedeff and Vinnikov *et al.* series are extended to 1991 and 1990 (data from the original authors). The Jones data differ slightly from the data used in S7 because an improved method was used to convert 1951-70 anomalies to 1951-80 anomalies. Smoothed curves in this supplement, except where otherwise described, use a 21 point binomial low pass filter as mentioned in paragraph 1 on p207 of S7. In the Jones data set, 1990 was the warmest year in the Northern Hemisphere record. In the Southern Hemisphere, 1991 appears to have been the warmest, because of anomalous warmth in Antarctica, but data for some areas are incomplete. For both hemispheres, the 1980s was the warmest decade in the entire record.

Warming due to urbanization may still affect these results but is probably not serious (S7, p 209). However, a physically-based analysis of the urbanization problem is still lacking; a recently published simplified physical model of urbanization warming indicates that the problem may be more complex than hitherto thought (Oke *et al.*, 1991). Jones *et al.* (1990) have compared rural-station temperature data sets over three large regions, European parts of the Soviet Union, eastern Australia and eastern China, with widely used hemispheric data sets. When combined with earlier analyses for the contiguous United States, the regions are representative of about 20% of the land area of the Northern Hemisphere and 10% of the Southern Hemisphere and contain some of the most heavily populated areas. They indicate that urbanization influences have yielded, on average, a warming of less than 0.05°C during the twentieth century over the global land. The reasons for this result are only partly understood but, for the Jones data set, they indicate that the station-by-station quality control procedures used were fairly successful.

C3.1.2 Hemispheric and Global Sea Surface Temperature

C3.1.2.1 Ship data

In S7 two Sea Surface Temperature (SST) analyses were used: those of Bottomley *et al.* (1990), up to 1989 and those of Farmer *et al.* (1989) up to 1986, the latter now discussed in Jones *et al.* (1991). Here we show an updated time-series that uses the Jones *et al.* data and a new UK Meteorological Office analysis to 1991. This new analysis combines the Bottomley *et al.* (1990) SST data base with some Comprehensive Ocean-Atmosphere Data Set (COADS) SST values. The COADS (Woodruff *et al.*, 1987) holds substantially more surface marine observations than does the data base created by Bottomley *et al.* (1990) but both sets contain unique data (Woodruff, 1990). The COADS were used to fill missing values in the fields of monthly Bottomley *et al.* (1990) SST data, mostly in the eastern half of the Pacific. Figure C3a shows the percentage of ocean covered by the new data and by the Bottomley *et al.* (1990) data. The new data reflect a substantial increase in coverage between the late 1870s and around 1910. Note that the new UK Meteorological Office SST data coverage exceeds that of the COADS. Improved instrumental corrections that use better models of heat transfers affecting wooden and canvas buckets have been used in the new UK Meteorological Office analysis as discussed in Folland (1991) and Folland and Parker (1992). The average magnitudes of these corrections, which vary geographically, with season and through time, are near 0.3°C (canvas buckets) and 0.1°C (wooden buckets). Although these values are small compared with the uncertainty in individual observations (Trenberth *et al.*, 1992) they are important when calculating the averages of thousands or more observations.

Another revision, that removes a little of the disagreement between Bottomley *et al.* (1990) and Farmer *et al.* (1989) data that was discussed in S7, is based on further evidence that wooden buckets may have been in predominant use at the beginning of the record. It is now assumed that 100% of buckets were wooden in 1856, the percentage linearly decreasing to 0% in 1920 (Folland and Parker, 1992). This transition from wooden to canvas buckets is nearly the same as that assumed by Farmer *et al.* (1989). However, since these authors assumed zero corrections for wooden buckets, appreciable differences between the two corrected data sets remain.

Although we feel justified in presenting a single best estimate of hemispheric and global SST changes since 1861 based on an average of the Jones *et al.* and UK Meteorological Office data (Figures C3b-d), we also show the smoothed curves for each data set. The new best estimate hemispheric and global SST curves generally lie between the continuous and dashed curves shown in Figures 7.8a and 7.8b of S7 (see note about Figure 7.8b in italics at the end of this sub-section). The addition of more Pacific data from the COADS in the late nineteenth century to the Bottomley *et al.* (1990) values has slightly increased the global average temperature in the UK Meteorological Office data set before 1900, and it remains warmer then than the Jones *et al.* data, largely owing to the positive wooden bucket corrections. Despite these "improvements", the uncertainty in the levels of nineteenth and early twentieth century SST due to data biases is 0.1°C at the least, the typical difference between the UK Meteorological Office and Jones *et al.* (1991) corrections at that time. This uncertainty increases markedly when the effects of data gaps are included.

Modern SST data may also contain non-trivial biases (Folland *et al.*, 1992), but only if these have changed significantly in recent decades would they affect **trends**. The fact that the many regional SST and night marine air temperature graphs shown in Bottomley *et al.* (1990) track

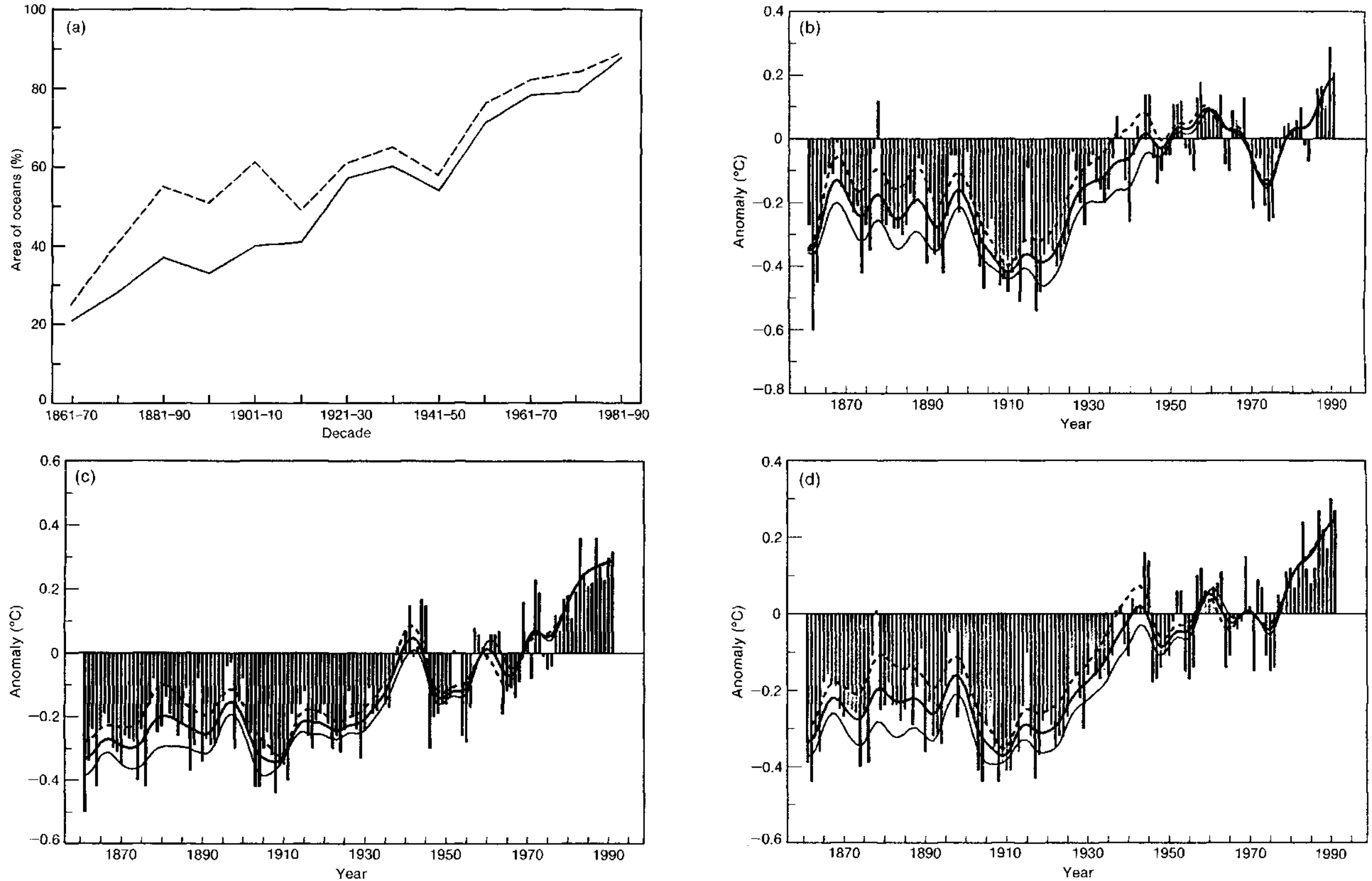


Figure C3: (a) Coverage of blended Bottomley *et al.* (1990) and COADS sea surface temperature data (dashed line) compared with that used by Bottomley *et al.* (1990) in S7 (solid line); (b) Time-series of Northern Hemisphere sea surface temperature anomalies relative to 1951-1980, based on the average of (i) an updated blend of Bottomley *et al.* (1990) and COADS, and (ii) data from Jones *et al.* (1991) (bars and heavy smoothed line). Separate smoothed series from (i) and (ii) shown by dashed and light solid lines respectively; (c) As (b) but for the Southern Hemisphere; (d) As (b) but for the Globe.

each other well in recent decades indicates that this is unlikely to be a serious problem.

Taken at face value, the increases of global mean SST between the periods 1861-1880, 1881-1900, 1901-1920, 1921-1940 and 1941-1960, and the single decade 1981-90, are now 0.43, 0.38, 0.50, 0.35 and 0.19°C respectively. This result highlights the irregularity of the warming which is largely concentrated in the periods 1920-1940 and 1975-1990 with sharp cooling between about 1900 and 1910.

Recently, Bates and Diaz (1991) have shown that even the present coverage of ship observations in the southern oceans south of 40°S is insufficient to adequately define the annual cycle of SST. Not surprisingly, therefore, SST anomaly time-series show that the Bottomley *et al.* (1990) 1951-80 climatology contains biases in parts of this area where very sparse data were blended with an earlier climatology. Though these biases probably do not much affect estimates of trends (Section C3.1.2.2), considerable uncertainty remains in Southern Hemisphere SST and SST anomaly estimates.

Due to a printing error, Figures 7.8b and 7.10b in S7 of IPCC 1990 referring to Southern Hemisphere temperatures were transposed. Thus, as printed, Figure 7.10b (p213) really shows Southern Hemisphere SST only and Figure 7.8b (p210) shows combined Southern Hemisphere SST and land air temperature.

C3.1.2.2 Reliability of the SST data

The causes and sizes of random errors in SST data have been studied by Trenberth *et al.* (1992) and Folland *et al.* (1992). They deduce that over many parts of the global ocean the signal of inter-monthly temperature variations is inadequately resolved even on large spatial scales. However, Folland *et al.* (1992) show that for seasonal averages over ocean basins, with the exception of areas south of 40°S, the resolved climatic signal is at least twice as great as the noise. For climate change and variability studies, there is an urgent need to extend these results to the annual, decadal, and century time-scales. "Frozen grid" tests show that estimates of global SST anomalies are only slightly more sensitive to changes in coverage than are the combined SST and land data. The latter (see S7, Figure 7.10d) show a surprisingly low sensitivity to the large changes in data coverage. But, as mentioned in S7, "frozen grid" tests do not adequately include the influence of those regions for which data has always been absent or very sparse, such as much of the Southern Ocean.

The SST data used in this document and in S7 are based on *in situ* observations from ships and buoys and, for the COADS, additional observations of near-surface temperatures from bathythermographs and recent data from the USA's Coastal-Marine Automated Network. During the past decade a new SST analysis has been created by blending data from satellite-borne infrared radiometers, for regions without *in situ* data (about 20% of the oceans), with *in situ* data elsewhere (Reynolds and Marsico, 1992). This blended analysis includes optimum interpolation (Gandin, 1963), takes explicit account of the presence of sea-ice and seems to successfully remove the temporally varying biases in satellite SST data relative to *in situ* data (Folland *et al.*, 1992). The identification of the satellite SST biases has resulted in a debate about the accuracy of the operational algorithms used to convert satellite radiance values to SST in the presence of atmospheric water vapour, cloudiness and episodes of global or regional contamination by volcanic or other aerosols (McClain *et al.*, 1985; Strong, 1989; Reynolds *et al.*, 1989; Bates and Diaz, 1991).

A comparison between the UK Meteorological Office *in situ* SST data and the Reynolds and Marsico data reveals a high correlation (r=0.94) between global, seasonally averaged anomalies during 1982-1990, but with a systematic difference of 0.1°C. The difference originates mostly in the Southern Hemisphere. The UK data are 0.16°C (0.03°C) warmer in the Southern (Northern) Hemisphere with a 0.85 (0.95) correlation of the seasonal anomalies. These differences originate near ice edges where they are much larger, and can be traced mainly to the fact that the Reynolds and Marsico analysis fixes SST at ice edges at -1.8°C, the average freezing point of sea water, while the UK analysis does not do this. The effects of this difference in methodology influence the analyses for some distance from the ice edges. Despite the differences, the interannual variability and the trends in the two data sets are very similar because the data bases contain much data common to both.

C3.1.2.3 Coral reef bleaching as an indicator of SST extremes

Increased reports of the bleaching of coral reefs may indicate higher SST values in many tropical regions over the last decade. The health of the coral reefs widely found through the shallow parts of tropical oceans is known to be sensitive to a number of factors, one of which is sea temperature in the top few tens of metres of the ocean (D'Elia *et al.*, 1991). Corals can tolerate a range of temperature without damage; outside this range damage is often exhibited as "bleaching". Bleaching occurs when green algae on which the coral depend are expelled from the cells of the coral when the latter are stressed. The tolerated temperature range varies with the species of coral, different species being adapted to given local conditions (D'Elia *et al.*, 1991). Thus bleaching can be a manifestation of a sea temperature that is extreme for the locality. However, local high temperatures may act with other stresses, such as pollution, to produce bleaching (Roberts, 1991). Recently many coral reef scientists have become convinced that bleaching due to elevated sea temperatures has become more common in the tropical oceans in the last decade (Brown, 1990; Glynn, 1991) though part of the increase may be due simply to better monitoring.

Several of the most severe events occurred in the tropical east Pacific and were related to the very strong 1982-1983 El Niño warming event when SST values increased several degrees above average values in this region. One hydrocoral species suffered a reduction of range, and another was probably made extinct (Glynn and de Weerdt, 1991). Since that time several other bleaching events have occurred, though not all can be related convincingly to available SST data. A more detailed comparison of coral reef bleaching and historical SST data is needed.

C3.1.3 Land and Sea Combined

Figures C4a-c show land data from the Jones analysis combined with the average of SST data from the new UK Meteorological Office analysis and the Jones et al. (1991) SST analysis for the Northern Hemisphere, Southern Hemisphere and globe respectively. The vertical bars are annual values. The method of combining the land and ocean data here is slightly different from that used in S7 (the latter is discussed in Folland, 1990). In Figures C4a-c land and ocean values have been combined more accurately and allow (approximately) for the relative areas of land and sea in every analysed grid box for every month. Figures C4a-c also show, as thinner lines, the analyses published in S7, for comparison. Values in the nineteenth century are very close to those shown in S7, and probably indistinguishably different allowing for uncertainties. The net effect of the changes is to make the long-term warming trends assessed in each hemisphere more nearly equal, with the Southern Hemisphere relatively marginally warmer in the late nineteenth century, especially around 1880, and the Northern Hemisphere unchanged. Compared to values shown in S7, larger differences in the last few years result from the addition of the warm years 1990 and 1991. S7, p212, cited increases of, or nominal linear trends in, temperature between various periods over the last century and a very recent period. A variety of warming rates occur, especially in the Northern Hemisphere. Here we note that the overall temperature increases over the globe, Northern and Southern Hemispheres between the twenty year period 1881-1900 and the latest decade 1981-90 are 0.47, 0.47 and 0.48°C respectively. This provides an estimate of the overall warming seen in the more reliable part of the instrumental record. Comparable values shown in S7 where the decade 1980-89 was compared with the twenty year period 1881-1900 were 0.45, 0.42 and 0.48°C respectively. To illustrate the small effect of including the least reliable earlier data, the estimated changes between 1861-80 and 1981-90 are 0.48, 0.42 and 0.56°C respectively. Differences between the two sets of changes should be regarded as being due to noise in the data. The difficulty of meaningfully calculating linear trends in these data is illustrated by Demarée (1990). He shows that the Jones Northern and Southern Hemisphere land air temperature records (Figures C2a and C2b) show a statistically significant "abrupt" change in their average values around 1920, though this may also reflect a rapid change in trend evident at that time (Section C4.2.3). This step-like character of the land-based temperature record was noted earlier by Kelly *et al.* (1985). Returning to the combined data in Figure C4, the global mean warming that commenced around 1975 represents an equally sudden change in trend from about zero to a rapid warming.

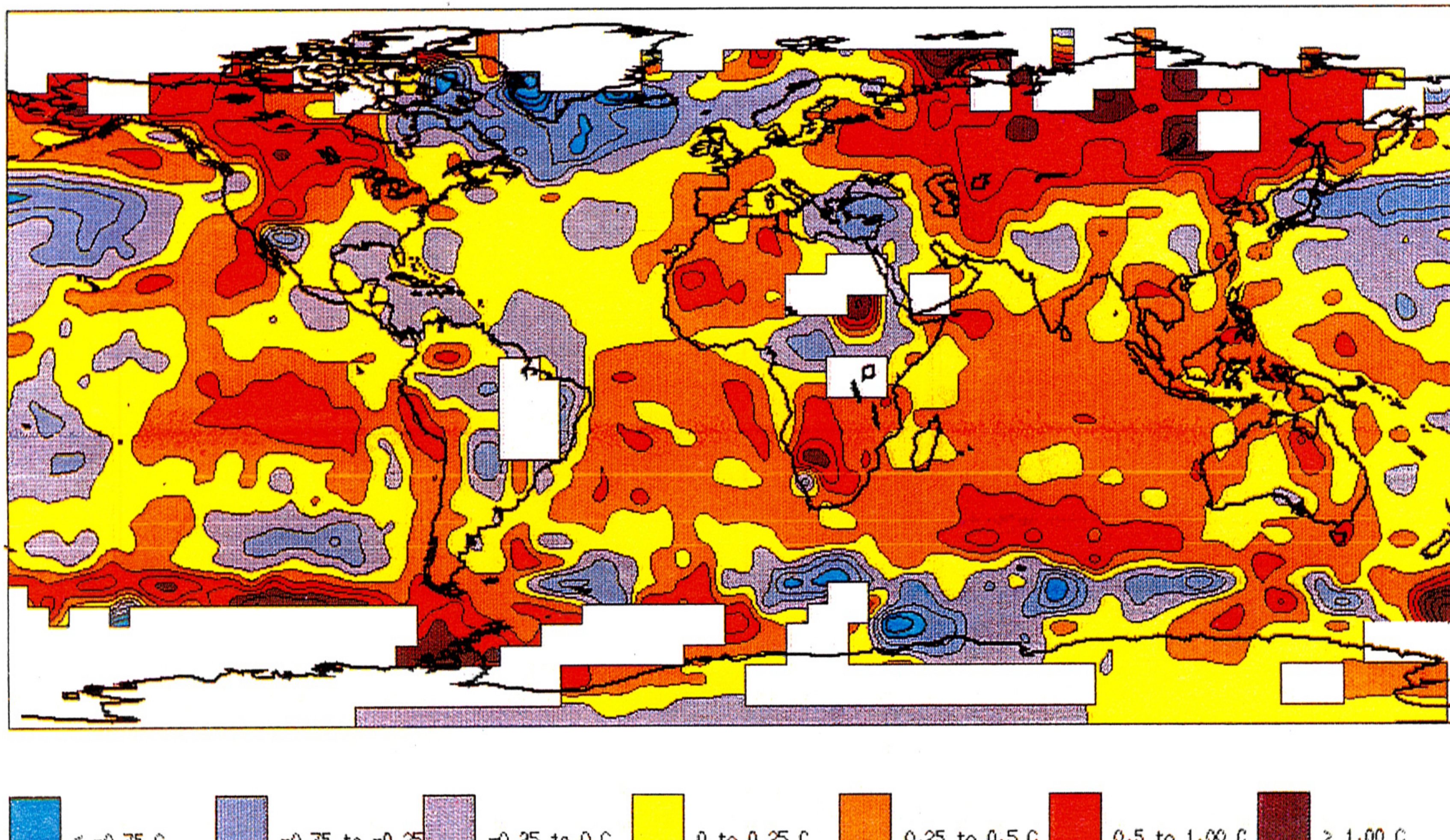
Figure C4d shows the coverage of the new combined data plotted against that used in S7. The increase reflects the increase in the UK Meteorological Office SST data coverage shown in Figure C3a. Notable is the strengthened representation of the very strong El Niño warm event of 1877-78 which, being sampled over a greater area, has had a greater effect on the hemispheric and global series.

1990 and 1991 are the warmest years in the combined land/ocean temperature record, while the 1980s is the warmest calendar decade. El Niño events are known to cause warming on a global and hemispheric average (S7, p227), but there was no clear El Niño event in 1990 in contrast to a pronounced event in 1986-7 and a very strong event in 1982-3. The reasons for the warmth of 1990 must mainly be sought elsewhere. However, 1991 did contain a pronounced El Niño event. It is known that atmospheric circulation anomalies played a part in 1990; a strong westerly atmospheric circulation over the Northern Hemisphere carried unusually warm air into Northern Eurasia in early 1990. Reduced snow cover (Section C3.4.1) is also likely to have contributed to the warmth, especially in March 1990, which was by far the warmest month in the entire Northern Hemisphere land anomaly record (Parker and Jones, 1991). Note that the ranking of individual years in the surface record is not exactly the same as for tropospheric data (see Section C3.3.1).

The difference in warming rate in recent decades in the two hemispheres is discussed in the context of possible aerosol and other effects in Section A and Section C4.2. The relative temperature anomalies are quantified in Table C1. Data for 1941-50 have not been included because of poor data coverage in the Second World War (see also Figure C4d). The difference in mean decadal anomaly changed markedly between 1946-55 and 1971-80, corresponding to a relative warming of the Southern Hemisphere compared to the Northern of nearly 0.3°C between these decades. This relative warmth of the Southern Hemisphere was greatest around 1975-1980 and

A SURFACE TEMPERATURE ANOMALIES wrt 1951-80

1981-1990



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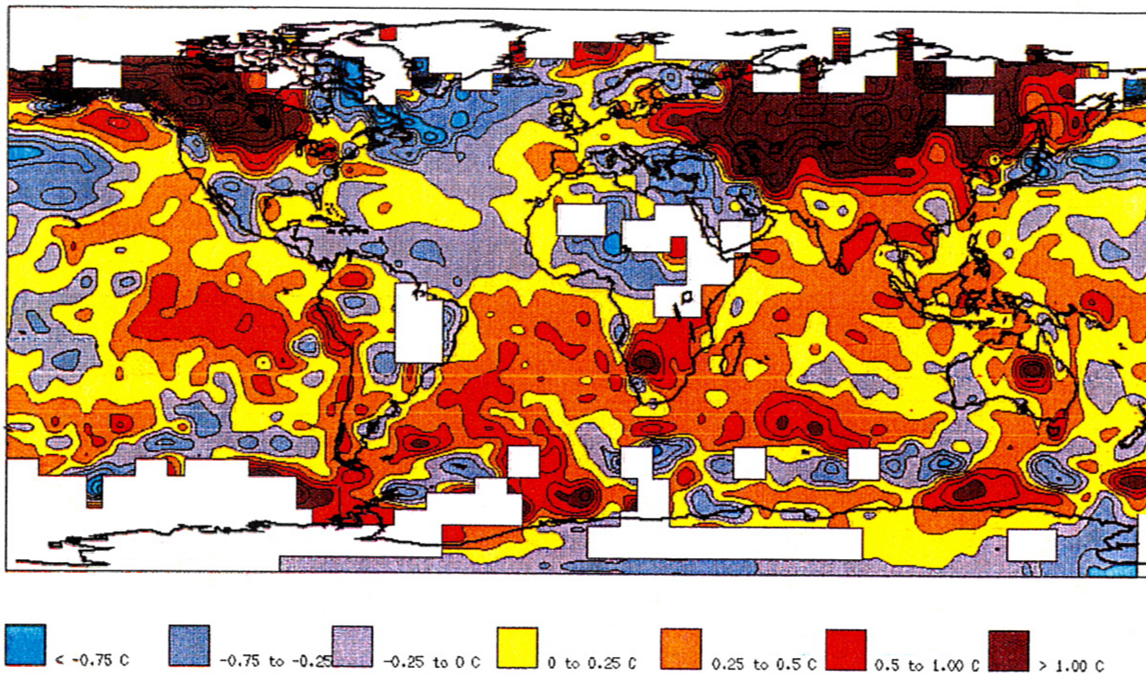
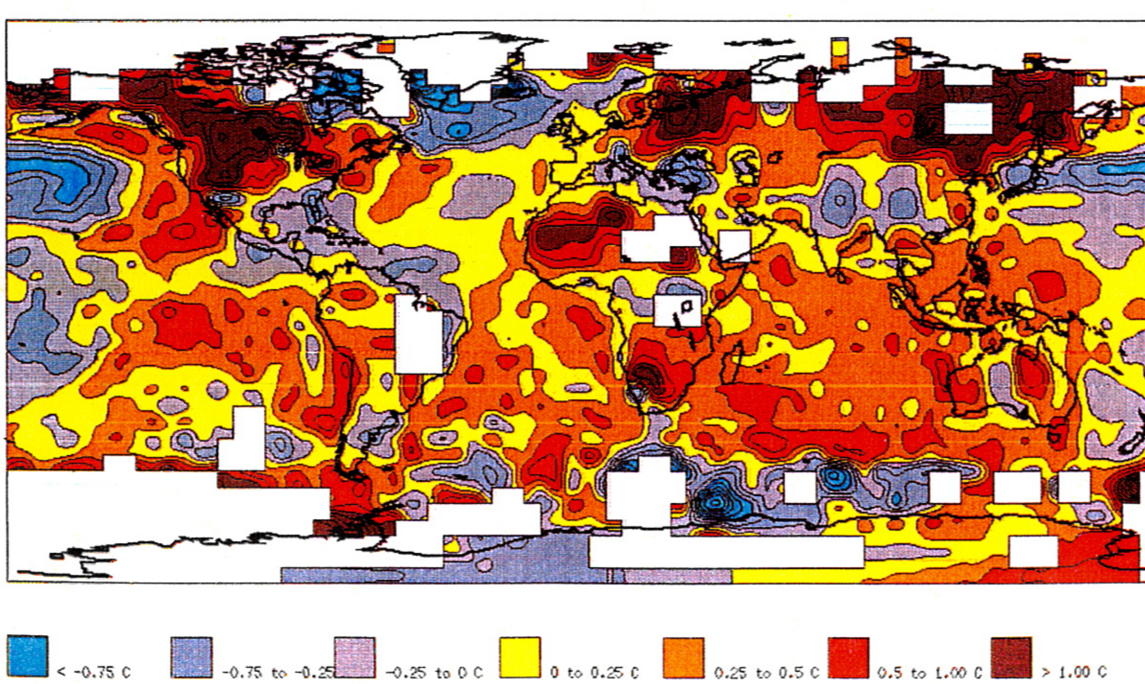
B SURFACE TEMPERATURE ANOMALIES wrt 1951-80
WINTER (Dec-Feb) 1981-1990



C SURFACE TEMPERATURE ANOMALIES wrt 1951-80
SPRING(Mar-May) 1981-1990



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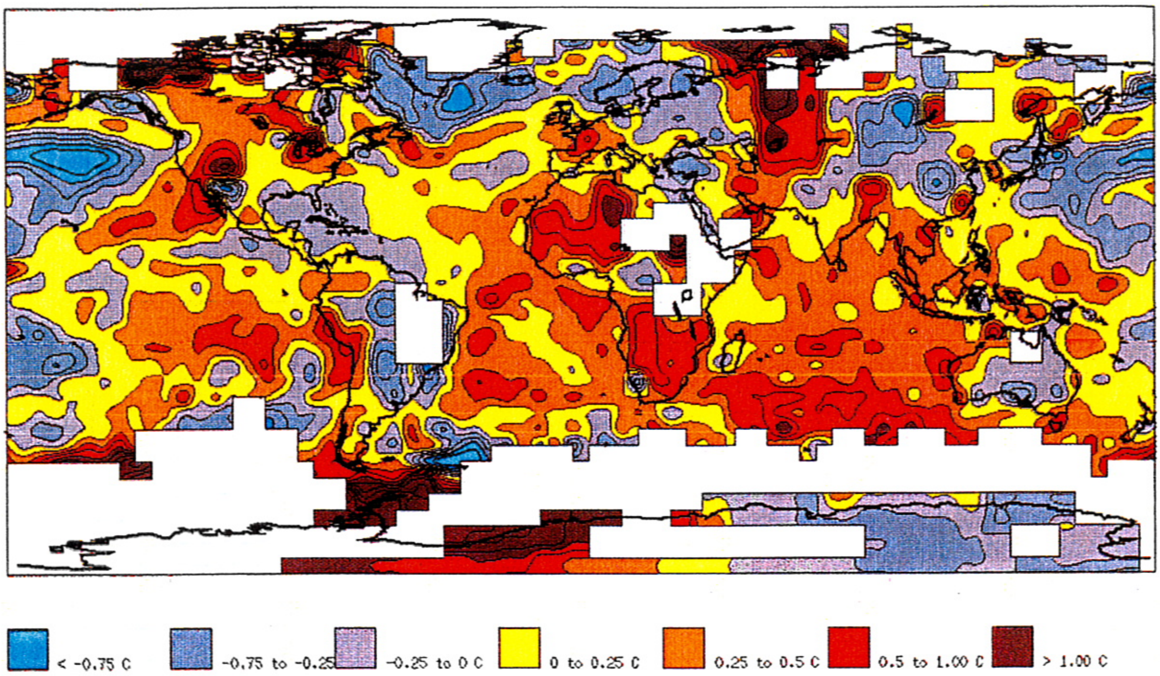
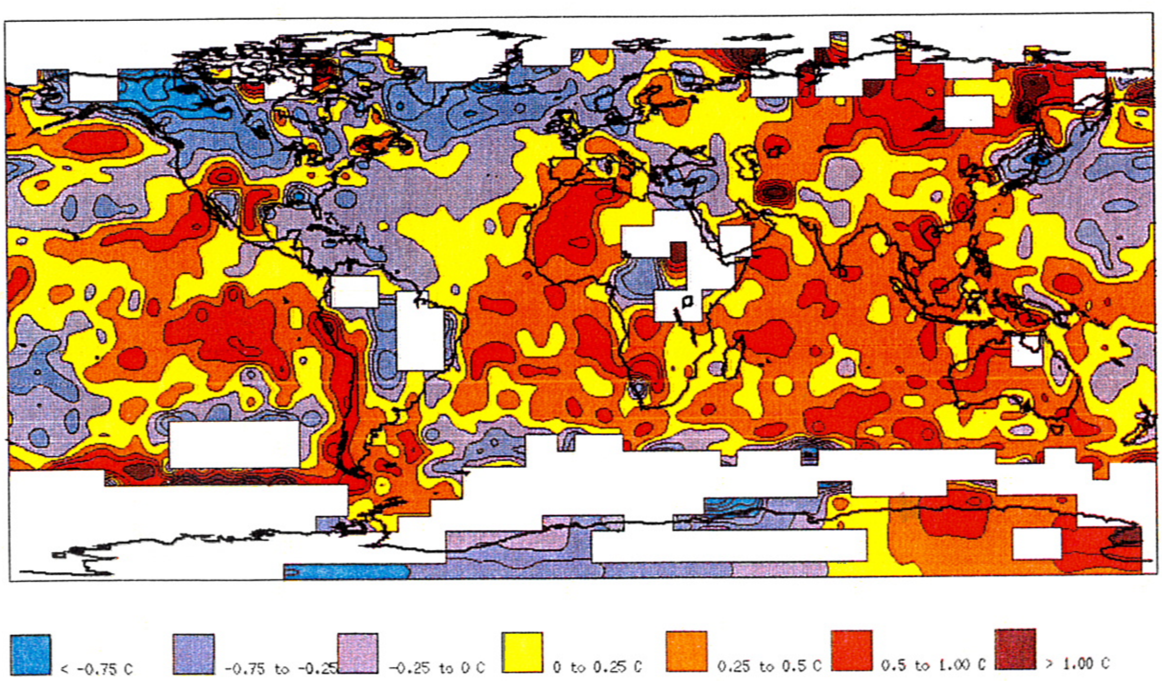
D SURFACE TEMPERATURE ANOMALIES wrt 1951-80
SUMMER(Jun-Aug) 1981-1990



E SURFACE TEMPERATURE ANOMALIES wrt 1951-80
AUTUMN(Sep-Nov) 1981-1990



(captions to plates D and E on page iv)

CAPTIONS TO FIGURES A, B, C, D and E

Figure C5 (A): Worldwide annual surface temperature anomaly patterns, 1981–1990, relative to 1951–1980. Sea surface temperature data are an updated blend of Bottomley *et al.* (1990) and COADS. Land air temperatures provided by Jones (1988, updated). A minimum of 6 three-month seasons (Jan–Mar, etc.) with at least one month's data was required in a 5° latitude × longitude box in each half-decade, in which there had also to be at least 3 years with data; otherwise the box was treated as missing. Seasonal anomalies were averaged within each half-decade, then the two half-decadal anomalies were averaged. See legend for contour details.

Figure C5 (B): As Figure C5(A) but for Dec–Feb. A minimum of 3 seasons with at least one month's data was required in a 5° latitude × longitude box in each half-decade; otherwise the box was treated as missing.

Figure C5 (C): As Figure C5(B) but for Mar–May.

Figure C5 (D): As Figure C5(B) but for June–Aug.

Figure C5 (E): As Figure C5(B) but for Sept–Nov.

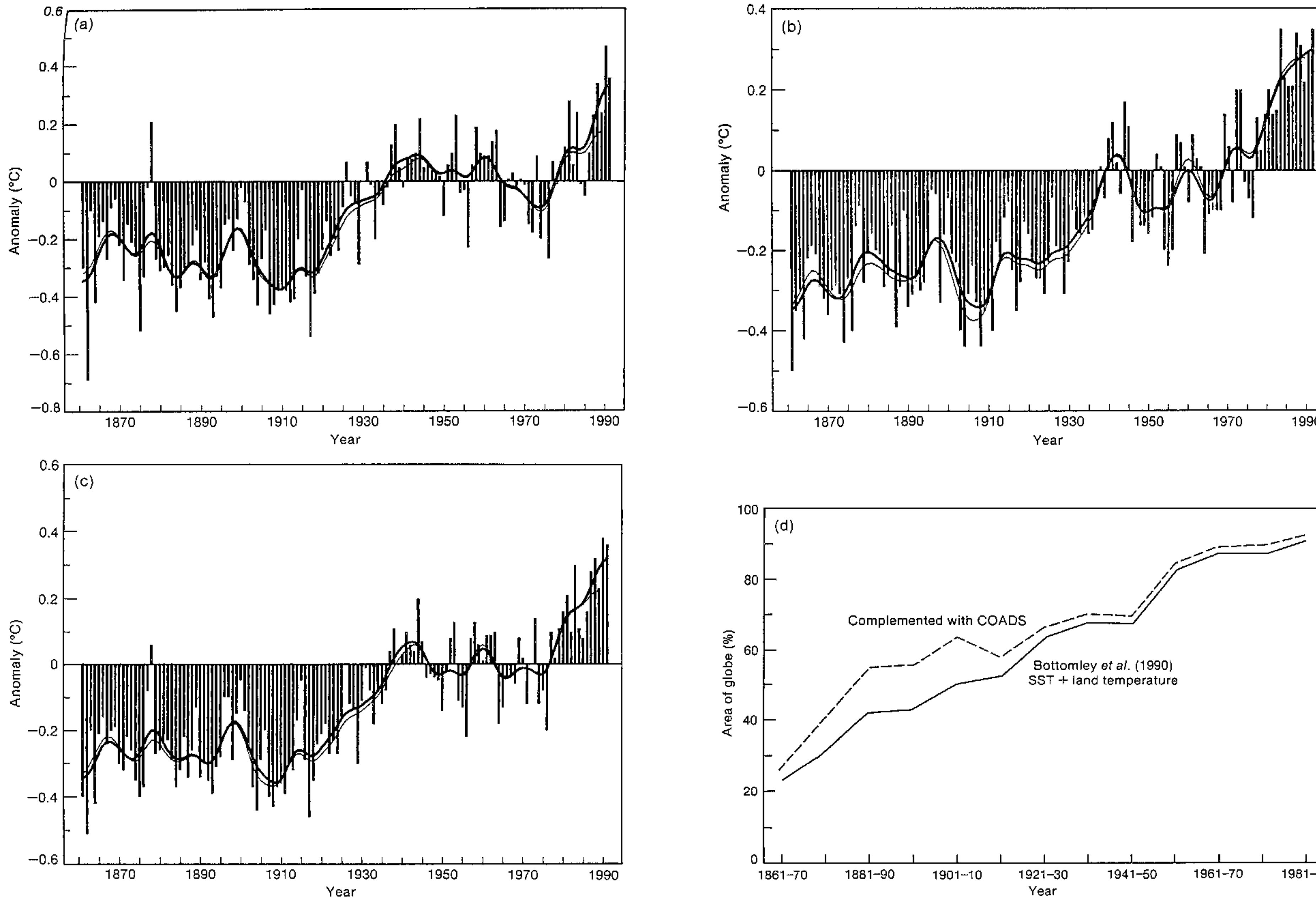


Figure C4: Combined land, air and sea surface temperature anomalies, 1861-1991, relative to 1951-1980. Land air temperatures are from Jones (1988, updated); sea surface temperatures are based on the average of (i) an updated blend of Bottomley *et al.* (1990) and COADS, and (ii) data from Jones *et al.*, 1991. Thick smoothed lines are from the updated data; thin lines are from S7: (a) Northern Hemisphere; (b) Southern Hemisphere; (c) Globe; (d) As Figure C3a but including land surface air temperature data.

Table C1: *Decadal mean surface temperature anomalies relative to 1951-80 in each hemisphere since 1946-55*

Decade	Northern Hemisphere (1)	Southern Hemisphere (2)	Difference (1)-(2)
1946-55	0.04	-0.12	0.16
1951-60	0.05	-0.06	0.11
1956-65	0.03	-0.03	0.06
1961-70	0.01	-0.03	0.04
1966-75	-0.05	0.01	-0.06
1971-80	-0.05	0.06	-0.11
1976-85	0.05	0.15	-0.10
1981-90	0.19	0.25	-0.06

the mean difference in anomalies in the last five years has returned to near zero. (The average anomalies for the three non-overlapping decades during 1951-80 are close to, but not exactly, zero due to progressive changes in data coverage.)

Considering the most recent and warmest decade, the sub-period 1986-1990 was warmer at the surface than 1981-85, though spatial patterns of temperature anomalies were, in the annual average, similar for each 5-year period. Positive anomalies in 1981-1990 were noticeably larger during December to May than in the rest of the year in both hemispheres (Figure C5). The El Niño-Southern Oscillation (ENSO) had a clear effect on the interannual variability of the global temperature, but does not explain all the observed patterns nor the fact that 1986-90 was warmer globally than 1981-1985, especially as 1986-1990 included the strong Pacific cold or "La Nina" event of 1988-1989. A cooling influence from the 1982 eruption of El Chichon may have affected the first five year period, though it is difficult to detect because of the strength of the contemporaneous 1982-83 El Niño.

C3.1.4 Worldwide Regional Temperature Anomaly Patterns

The spatial pattern of temperature anomalies at the Earth's surface for the decade 1981-1990, relative to a 1951-1980 climatology, is shown in Figure C5a. This is similar to that for 1980-1989 shown in Figure 7.13(c) of S7 and uses the UK Meteorological Office SST analysis for its ocean component. The decadal mean anomaly was assessed to be 0.22°C. Inclusion of COADS data has improved coverage over the Southern Ocean slightly. This ocean shows contrasting areas of positive and negative anomalies which may partly reflect noise in the Bottomley *et al.* (1990) 1951-80 SST climatology there. Some of the other local signals may also be affected by noise but it is not possible to quantify these problems yet (see Section C3.1.2.2 and Trenberth *et al.* (1992)). Notable are the warmth over the middle and high latitude continents in the Northern Hemisphere, the cool anomalies over the north-west extratropical Atlantic and the predominant warmth of the Southern Hemisphere where data exist. Also shown (Figures C5b-e) are the anomalies for the constituent three-month seasons. The boreal winter map is an average from Dec 1980-Feb 1981 to Dec 1989-Feb 1990, boreal spring for Mar 1981-May 1981 to Mar 1990-May 1990, etc. Notable features are:

(1) Dec-Feb - very large areas of positive anomalies exceeding 1°C over the high latitude Northern Hemisphere continents, with centres over 2°C, separated by notably negative anomalies over the northwestern North Atlantic, including the area around south Greenland, and also the mid-latitude North Pacific. The USA shows negative anomalies in the south, with positive anomalies near Canada. Positive anomalies over the Antarctic Peninsula are generally near 0.5°C. The global mean anomaly was 0.26°C (the most positive seasonal mean anomaly).

(2) Mar-May - a broadly similar pattern but with a smaller area of high latitude Northern Hemisphere anomalies exceeding 1°C and positive anomalies over North Africa. Positive anomalies over the Antarctic Peninsula are stronger than in December to February. USA anomalies are positive away from the southern states, notably over the Rockies with values mostly exceeding 1°C there. The global mean anomaly was 0.24°C.

(3) June-Aug - a broadly similar pattern to spring except that both negative and positive anomalies are seen over high latitude Asia, giving a small overall positive anomaly. Positive anomalies over the Antarctic Peninsula are at their strongest, averaging around 2°C. Anomalies over the USA are mixed but

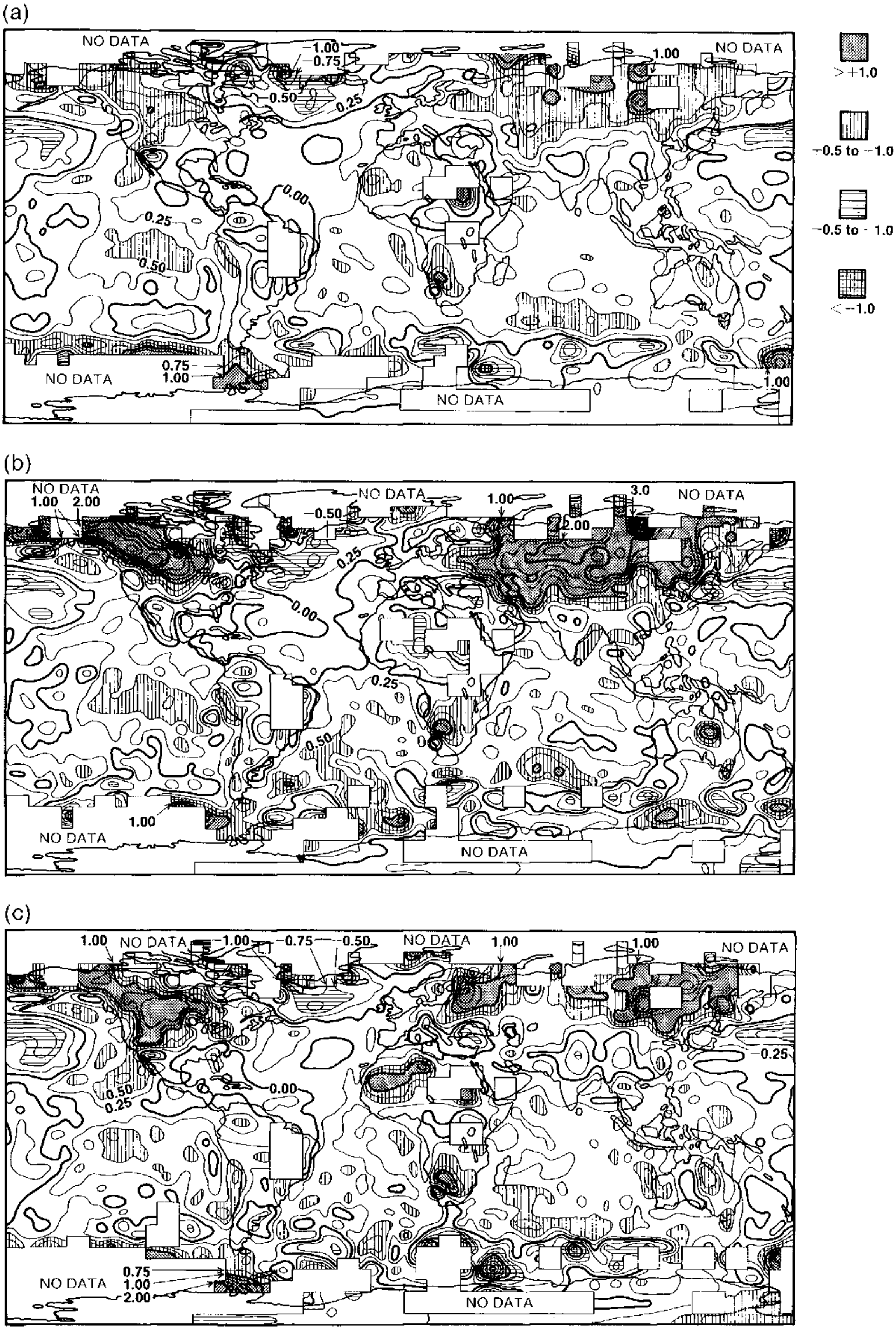


Figure C5: (a) Worldwide annual surface temperature anomaly patterns, 1981-1990, relative to 1951-1980. Sea surface temperature data are an updated blend of Bottomley *et al.* (1990) and COADS. Land air temperatures provided by Jones (1988, updated). A minimum of 6 three-month seasons (Jan-Mar, etc.) with at least one month's data was required in a 5° latitude × longitude box in each half-decade, in which there had also to be at least 3 years with data; otherwise the box was treated as missing. Seasonal anomalies were averaged within each half-decade, then the two half-decadal anomalies were averaged. Vertical hatching >0.5°C, stippling >1°C, horizontal hatching <-0.5°C, cross-hatching <-1°C. Also shown in the colour section. (Captions for (b) and (c) continued on next page.)

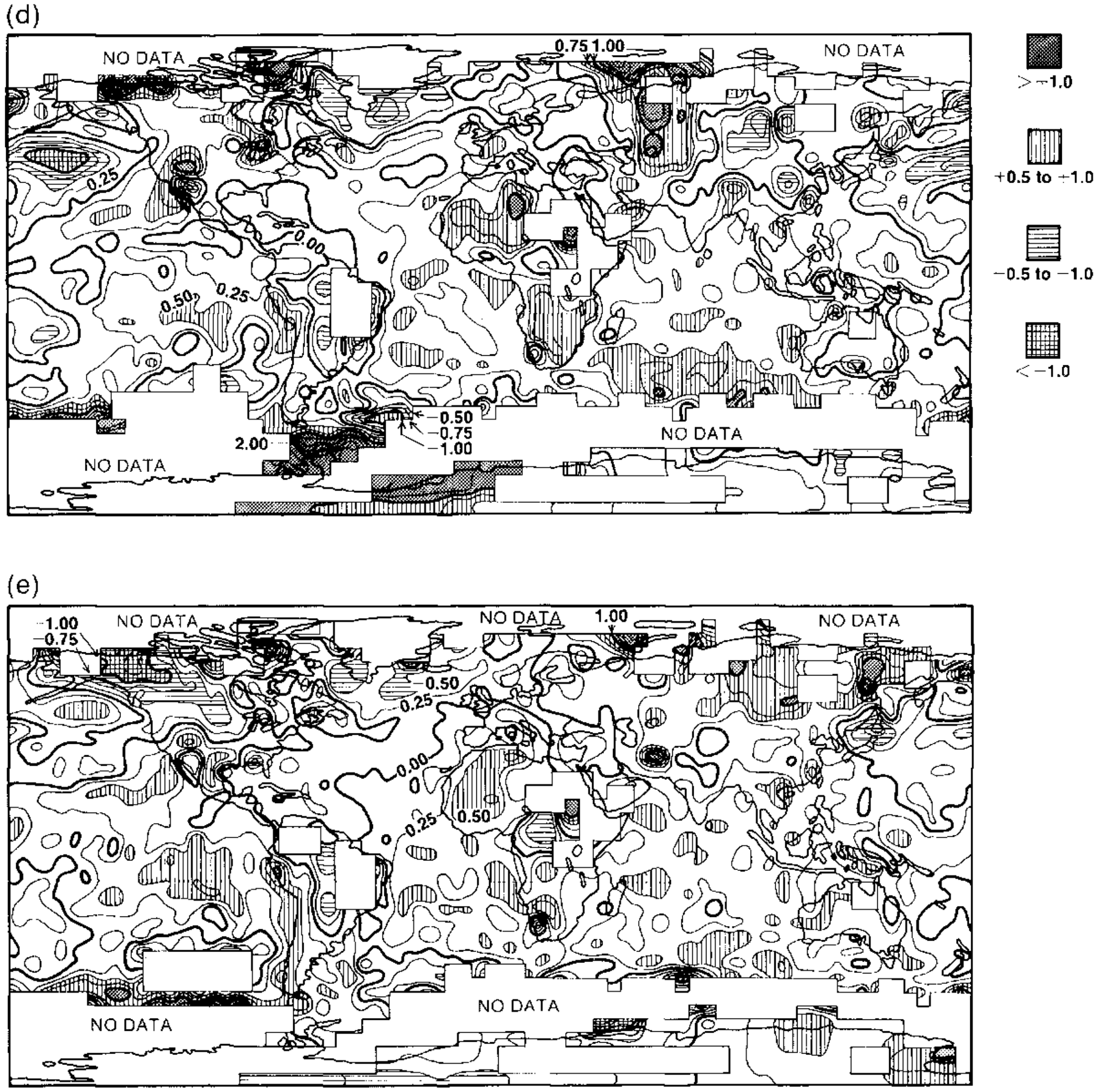


Figure C5: (b) As Figure C5a but for Dec-Feb. A minimum of 3 seasons with at least one month's data was required in a 5° latitude by longitude box in each half-decade; otherwise the box was treated as missing; (c) As Figure C5b but for Mar-May; (d) As Figure C5b but for June-Aug; (e) As Figure C5b but for Sept-Nov. Also shown in the colour section.

positive on average away from southern-most states. The global mean anomaly was 0.20°C.

(4) Sept-Nov - major differences from summer are the negative anomalies over Alaska and most of Canada, widely cooler than -0.5°C. High latitude Asian anomalies are generally positive with a pattern rather like that of spring, but weaker. Antarctic Peninsula anomalies are weak. USA anomalies are weak and average to near zero. The global mean anomaly was 0.17°C (the least positive seasonal mean anomaly).

New land temperature series from the South Pacific and eastern Australia show that the 1980s was the warmest decade on record (Salinger and Collen, 1991; Plummer, 1991). Temperature trends in the South Pacific come from sites where there can be little question of an urban influence. Many records are from island or remote rural sites. Land surface temperatures in eastern Australia and the South-West Pacific west of the South Pacific Convergence Zone (SPCZ) increased from the 1940s until 1990 by between 0.5° and 1.0°C. The area east of the SPCZ in the central South Pacific showed a temperature decline between 1945 and 1970, with a rapid temperature increase during the 1980s.

Temperature changes in recent decades in China have been regionally and seasonally specific (Chen *et al.*, 1991). Thus the 1980s were up to 1°C warmer than the 1951-1980 climatology in Northern China, but up to 0.5° colder in a few locations in Southern China.

Note that in Figure 7.13(c) of S7 (IPCC, 1990), *Antarctic air temperature anomalies were erroneously reduced to one tenth of their true value; this has been rectified in Figure C5. The main effect of this error was virtually to eliminate large positive anomalies (up to 1°C) over the Antarctic Peninsula. Anomalies were small elsewhere over Antarctica.*

C3.1.5 Changes in the Diurnal Range of Temperature

S7 (p217) provided evidence that maximum temperatures in the USA, south-eastern Australia and China remained nearly stationary over the past several decades, but an increase of minimum temperatures was quite apparent. Karl *et al.* (1991b) have extended these time-series to include the USSR and have updated the Chinese and USA series (Figure C6). Over the last four decades, the results indicate large increases of daily minimum temperatures (0.1°C/decade) but little change of the daily maximum temperatures. Karl *et al.* (1991b) also found trends in seasonal extremes of the maximum and minimum similar to the changes of the mean maximum and minimum. Preliminary analyses for Canada and Alaska give similar results. It is unclear whether this phenomenon is global, but it is certainly a characteristic of a substantial part of the Northern Hemisphere record. However Mifsud (personal communication) finds a notable **increase** in the diurnal range in Malta over the last 60 years and Bücher and Dessens (1991), while describing a marked decrease in the diurnal range at a mountain-top station in the Pyrenees, also note that the mountain-top Sonnblick (Austria) record does not show such a change.

The results of Karl *et al.* (1991b) for the USA, the USSR, and China are appropriately area-weighted and aggregated in Table C2, which shows that the annual rate of warming is 3 to 10 times greater at night than by day, depending on the period of record chosen. Overall, summer maximum temperatures appear to have decreased in these regions.

Section 2 (S2: sub-section 2.3; Shine *et al.*, 1990) and Section A of this report describe mechanisms for increases of cloud cover, cloud albedo, and clear-sky albedo because of observed increases in sulphate aerosol. If this were occurring, there would likely be a preferential cooling effect by day, possibly leading to a reduced diurnal range in the Northern Hemisphere. This conclusion is consistent with the above results and with the finding of S7 that there was no decline in the mean daily temperature range over interior Australia and New Zealand.

Despite the known problems with changes in cloud observation practices and codes, it is likely that widely observed increases in cloud cover (S7, p230; Henderson-Sellers, 1990) have contributed to the reduced diurnal range (Plantico *et al.*, 1990; Bücher and Dessens, 1991), though not everywhere. Decreases of sunshine have been found in Germany (Weber, 1990) and the diminution of

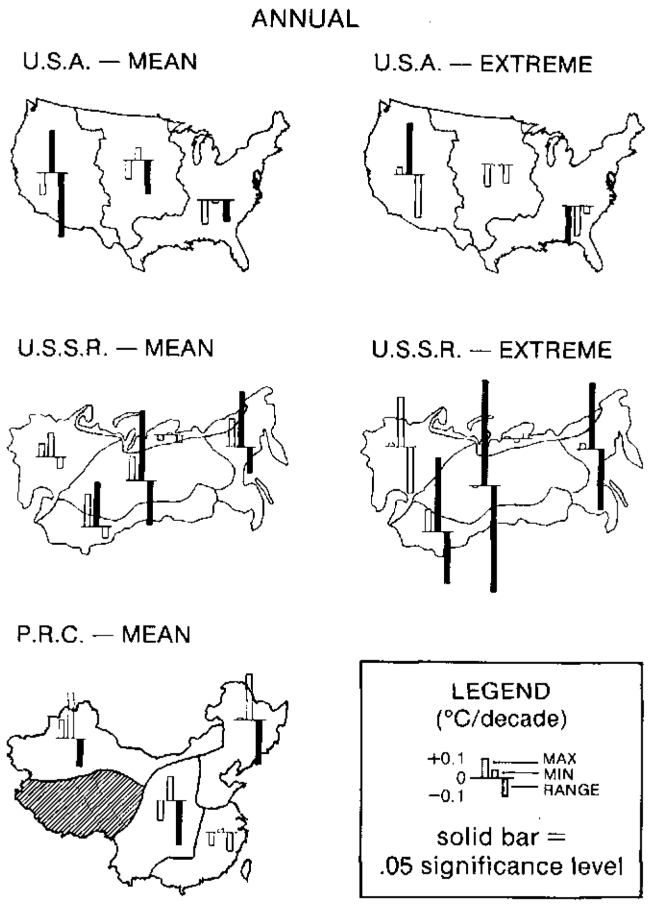


Figure C6: Trends of annual mean daily maximum and minimum temperatures and diurnal range (left) and of seasonal extreme temperatures and their differences (right). Solid bars are statistically significant at the 95% confidence level using a two tailed t-test. Data start in 1951 and finish in 1990 (USA), 1988 (China) and 1986 (USSR). There are no data available for the shaded area of southwest China.

ultraviolet radiation at low altitudes (Scotto *et al.*, 1988) coupled with enhancement at high elevation (Bruhl and Crutzen, 1989) suggests some type of increase in a lower tropospheric scattering agent.

Whatever the exact cause of the decrease in the diurnal temperature range (urbanization effects cannot be excluded and atmospheric circulation changes might also be contributing), there is an increasingly urgent need to reinterpret the global land record, at least regionally, in terms of changes in maximum (daytime) and minimum (night-time) temperatures. Care will need to be taken that artificial changes in the diurnal range are properly accounted for, such as have already been done for the USA where progressive automation of the climate observing network has taken place accompanied by a change of thermometer screen (Quayle *et al.*, 1991). The resulting non-climate related mean change in measured diurnal range over the USA is assessed to be -0.7°C (note that Karl

Table C2: *Area-weighted aggregate of temperature trends, °C/100 years (°C/40 years) for the USA, USSR and Peoples' Republic of China*
a) Using records for 1951-90 (USA), 1951-86 (USSR), 1951-88 (China)

Season	Mean maximum (day)	Mean minimum (night)	Mean max minus min (diurnal range)
Winter	0.7 (0.3)	2.4 (1.0)	-1.7 (-0.7)
Spring	2.1 (0.8)	3.2 (1.3)	-1.2 (-0.5)
Summer	-0.7 (-0.3)	0.5 (0.2)	-1.2 (-0.5)
Autumn	0.1 (0.0)	2.2 (0.9)	-2.0 (-0.8)
Annual	0.6 (0.2)	2.0 (0.8)	-1.5 (-0.6)

b) Using records for 1901-90 (USA), 1936-86 (USSR), 1951-88 (China)

Season	Mean maximum (day)	Mean minimum (night)	Mean max minus min (diurnal range)
Winter	0.6 (0.2)	1.8 (0.7)	-1.2 (-0.5)
Spring	0.6 (0.2)	1.5 (0.6)	-0.8 (-0.3)
Summer	-0.4 (-0.2)	0.4 (0.2)	-0.8 (-0.3)
Autumn	-0.6 (-0.2)	0.7 (0.3)	-1.2 (-0.5)
Annual	0.1 (0.0)	1.1 (0.4)	-0.9 (-0.4)

et al., 1991b, analysed the corrected USA data). Meanwhile, there is a need for comparisons with results from general circulation models forced with increased greenhouse gases. Section B4.2 gives an initial discussion.

C3.2 Precipitation and Evaporation Variations and Changes

For many areas, the variability of precipitation is so large that it is virtually impossible to detect important changes until well after the occurrence of changes that have practical (e.g., agricultural or economic) significance. This is highlighted in recent work by Karl *et al.* (1991a) for the USA and Nicholls and Lavery (1992) for Australia.

C3.2.1 Precipitation Over Land

As discussed in S7, p220, raingauges have tended to underestimate precipitation, particularly snowfall (solid precipitation). Legates and Willmott (1990) and Soviet researchers (World Water Balance, 1978) have estimated that global precipitation over land is on average underestimated by 10% to 15%. Progressive improvements to instrumentation have tried to remedy this and have introduced artificial, systematic, increases in precipitation. Recent efforts to automate measurements may again be reversing this trend. Thus long-term variations and trends should be interpreted cautiously.

A selection of regional time-series was given in S7 (p219). These have been updated, but no new conclusions can be drawn. For example, precipitation over the Sahel region of North Africa (Figure 7.16b of S7) has remained well below the long-term average in 1990 and 1991 (Rowell *et al.*, 1992), extending the drought epoch there into its third decade. Changes in rainfall in the Sahel have been much larger than can be accounted for by instrumental problems. The Sahel has experienced the largest observed regional percentage change in precipitation between the two thirty year periods 1931-60 and 1961-1990: a decline of 30% (Hulme *et al.*, 1992). The latter period includes the relatively moist 1960s (S7, Figure 7.16b and Demarée and Nicolis, 1990), so the "real" change in average since 1931-1960 may be larger. The only other major region known to show a notable long-term trend in precipitation is the USSR (Figure 7.16a of S7). Area-averaged precipitation over the same region (37°-70°N, 25°-140°E) has recently been revised to eliminate minor spurious trends and updated to 1990 (Groisman *et al.*, 1991). Overall, the effects of these corrections are small and the conclusion in S7 that there has been a notable increase of precipitation over the USSR south of 70°N during the last century is unaffected.

Although a number of regional rainfall fluctuations on decadal time-scales have been found, some of practical significance, there is, as yet, no firm new evidence of global-scale multidecadal rainfall trends.

C3.2.2 Precipitation Over the Oceans

In S7, p220, a discussion was presented concerning the likelihood that precipitation had increased over the global tropical oceans since 1974, based on an analysis of satellite outgoing longwave radiation (OLR) data by Nitta and Yamada (1989), with an opposing opinion expressed by Arkin and Chelliah (1990). Chelliah and Arkin (1992) have now shown that much of the decreasing trend in OLR between 1974 and 1991, which appears to indicate an increase of tropical oceanic rainfall, can be unambiguously related to satellite instrumental factors rather than a real OLR increase. Therefore an increase in rainfall over the tropical oceans since 1974 remains unproven.

C3.2.3 Evaporation from the Ocean Surface

Estimates of trends in evaporation over the ocean are unlikely to be reliable until constant biases (Isemer and Hasse, 1991) and time-varying biases in wind speed measurement are properly accounted for (Cardone *et al.*, 1990; Ward, 1992; S7, Section 7.5.3, p220), and a proper treatment of ocean temperature at the surface interface (the ocean "skin") is included. In addition, the uncertainties in SST, near-surface air temperature and humidity data must all be allowed for, especially as estimates of evaporation changes made so far include ship-measured daytime air temperature data which may have considerable absolute and some time-varying biases as discussed in S7, p211. Furthermore, inadequate ventilation of some thermometer screens on ships, and the effect of the ship itself, can affect calculations of specific humidity. Despite these data problems, two studies have recently been made of latent heat flux trends, with some allowances for artificial trends in wind speed data. Because an increase in evaporation associated with warming is potentially a very important climatic feedback, we discuss these studies despite their drawbacks.

Following initial calculations that appeared to show an increase of the evaporation rate from parts of the tropical oceans between 1949 and 1979 (Flohn *et al.*, 1990a, b), a revised analysis has been carried out to investigate the sensitivity of the results to varying assumptions about the reality of increasing near-surface wind speed over the oceans (Flohn *et al.*, 1992). Figure C7a shows calculations of the evaporation trend in the tropical oceans between 10°S and 14°N, expressed as a linear rate between 1949 and 1989. Only the main shipping lanes have been studied. If it is assumed that the observed near-surface wind speed trends should be reduced to 50% of their measured values over the areas sampled, an average increase of about 18Wm^{-2} of heat input into the atmosphere is implied over the belt as a whole. Calculations for sub-sections of the zone (warmest oceans, upwelling regions and Atlantic sector) give similar results.

In a further study, Fu and Diaz (1992) show an apparent upward trend of about 1% per year in integrated mean oceanic latent heat flux during the period 1978-1989. This increase (curve a in Figure C7b) is due primarily to an overall increase in reported wind speed over the global oceans of about 0.5 ms^{-1}. Allowing for an artificial component in the increase of wind speed (Cardone *et al.*, 1990), it is estimated that the observed wind speed trend should be reduced to between 65% and 50% of its apparent value, giving the reduced trend in latent heat flux shown in curve b of Figure C7b. This corresponds to a global increase in latent heat flux into the atmosphere between 1978 and 1988 near 5Wm^{-2}/decade. Similar results are obtained by Flohn *et al.* (1992) over part of the tropical North Atlantic. Although there is no indication of bias in the surface pressure measurements, possible hidden trends

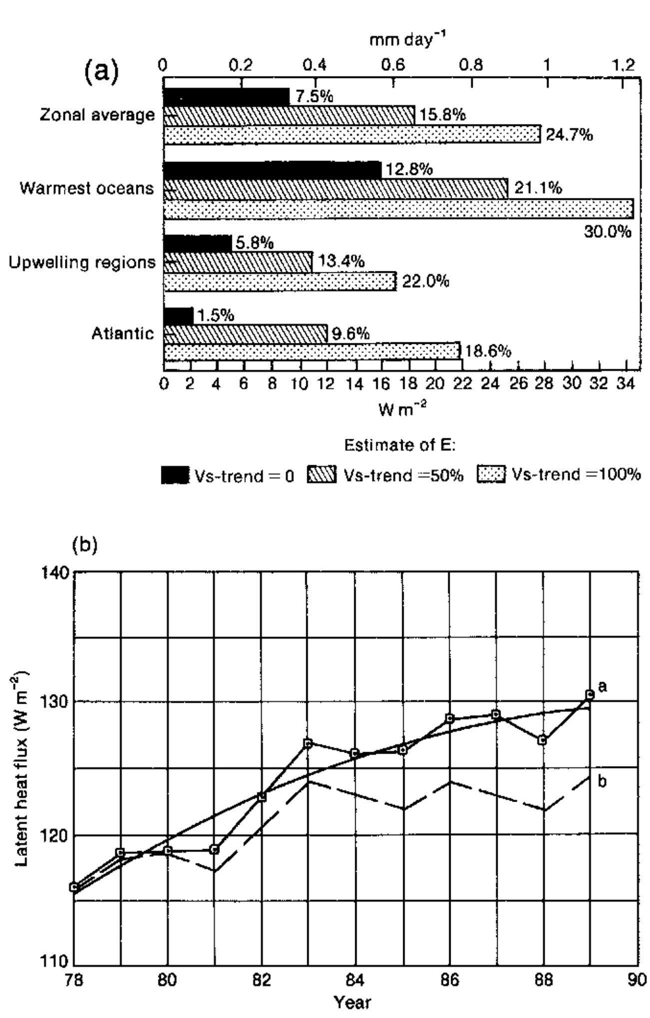


Figure C7: (a) Changes in evaporation rate, E, from the tropical oceans (10°S-14°N) between 1949 and 1989, based on COADS data after multiplying the wind speed trend, Vs, by zero, 0.5 and 1.0. Taken from Flohn *et al.* (1992): (i) whole zone; (ii) warmest oceans (66°E-160°E); (iii) upwelling regions, and (iv) Atlantic sector; (b) Trends in global annual oceanic latent heat flux (Wm^{-2}), 62°N-42°S from Fu and Diaz (1992). Curve a (and smoothed curve): using unadjusted winds; Curve b: using winds reduced following Cardone *et al.* (1990).

in pressure gradients in Fu and Quan's analyses due to variations in data sampling need investigation. Overall, it is uncertain whether the apparent enhancement of evaporation from the global oceans shown in Figures C7a and b is a real climatic signal that has accompanied the recent global oceanic warming seen in Figures C3 and C5.

An increase of tropical precipitation might be expected to accompany increases in evaporation. However, the results of Chelliah and Arkin (1992) discussed in Section C3.2.2 do not confirm this idea. So, although an increase in the hydrological cycle in the last 10-20 years is plausible, it is not proven. A rigorous analysis of the physical consistency of the local values of, and trends in, the various data used to calculate evaporation is essential for further progress.

C3.3 Tropospheric and Lower Stratospheric Variations and Change

C3.3.1 Temperature

C3.3.1.1 Radiosonde data

There are now two independently-derived data sets, that of Angell (1988) used in S7 (p220-222) and a new compilation due to Oort and Liu (OL) (1992). Both data sets may suffer from data-quality problems, because adequate studies of possible time-varying biases in radiosonde temperature data have not been made (Elliott and Gaffen, 1991). The annual data derived from the Angell analysis uses a different definition of the calendar year from all other analyses in Section C, being based on December-November. This will slightly reduce correlations between annual values of the Angell and other data sets. Unless otherwise stated, the term "lower stratosphere" used in the remainder of Section C refers to that part of the atmosphere between the 50 and 100 hPa levels.

The spatial representativeness of the Angell radiosonde data set has been examined by Trenberth and Olson (1991) in a study of how well the widely spread but sparse 63-station network describes regional and global climatic changes. By comparing its interseasonal and interannual climatic statistics over 1979-1987 with those from a complete global data set provided by the European Centre for Medium Range Weather Forecasts, they found that correlations between the two data sets were generally quite high, but that root-mean-square errors for Angell's extratropical zones were of the same order as the interannual climatic signals being studied. Angell's data also showed systematically enhanced interseasonal and interannual variability in the extratropics because of the limited spatial sampling.

The OL data are derived from up to 800 individual site records from the global radiosonde network interpolated onto a regular latitude-longitude grid. In terms of data density, the OL data base is therefore an improvement on that of Angell.

Figures C8a-c present updated annual global series of temperature anomalies from a 1964-1989 average for the surface and 850-300 hPa layer (a), the 300-100 hPa layer (b), and the 100-50 hPa layer (c), using Figure C4 for the surface. The data sets are, unfortunately, short but are important because they have been used in initial studies of the greenhouse-gas detection problem (Section C4). Although the radiosonde coverage is adequate from 1958 in the Northern Hemisphere, it is only complete enough in the Southern Hemisphere since 1964. Global values can therefore only be estimated since 1964, though Angell used incomplete Southern Hemisphere data to extend his global series back to 1958.

Correlations (1964-1989) between the OL and Angell annual global series are high, 0.97, 0.91 and 0.90 at 850-300 hPa, 300-100 hPa and 100-50 hPa respectively. However, the absence of some extensive areas may have allowed higher correlations than would be obtained between either series and a globally-complete series. Note that surface values show substantially less interannual variability. The correlation between the annual OL 850-300 hPa series and the surface (ocean and land) series is 0.94; Angell's series show slightly greater interannual variability than that of OL for the globe and (not shown) for both hemispheres. Angell's data also tend to show greater cooling than those of OL in the 300-100 hPa layer, mainly in the Northern Hemisphere but also in the Southern Hemisphere lower stratosphere 100-50 hPa layer, but less cooling in the 100-50 hPa layer in the Northern Hemisphere. OL's trends in annual mean temperature for the globe were 0.21, -0.08 and -0.41°C/decade (1964-1989) for the three layers in ascending height order, with similar trends in each hemisphere. Angell's corresponding trends for the period 1964-1991 were 0.24, -0.16 and -0.52°C/decade. Combining values from the two analyses by using the more comprehensive OL data to 1989 and the Angell data in 1990 and 1991, our best estimate for trends in the three layers between 1964 and 1991 are Northern Hemisphere: 0.21, -0.05 and -0.38°C/ decade; Southern Hemisphere: 0.23, -0.13 and -0.53°C/ decade and Globe: 0.22, -0.09 and -0.45°C/decade. The trend in the surface data over this period was 0.16°C/decade.

The warming trend in the mid-tropospheric layer and the cooling trend in the lower stratosphere are significant in both data sets at better than the 1% level, allowing for autocorrelation of the data. The warming trend at the syrface is also significant at the 1% level. However, the cooling trend in the globally-averaged 50-100 hPa layer may be exaggerated because the data begin in 1964 which was very warm in the tropical stratosphere following the eruption of Agung in 1963 (Newell, 1970). Inspection of Figure C8 suggests that after the influence of Agung has been removed, a slow cooling trend followed until 1982 when a temporary warming occurred due to the eruption

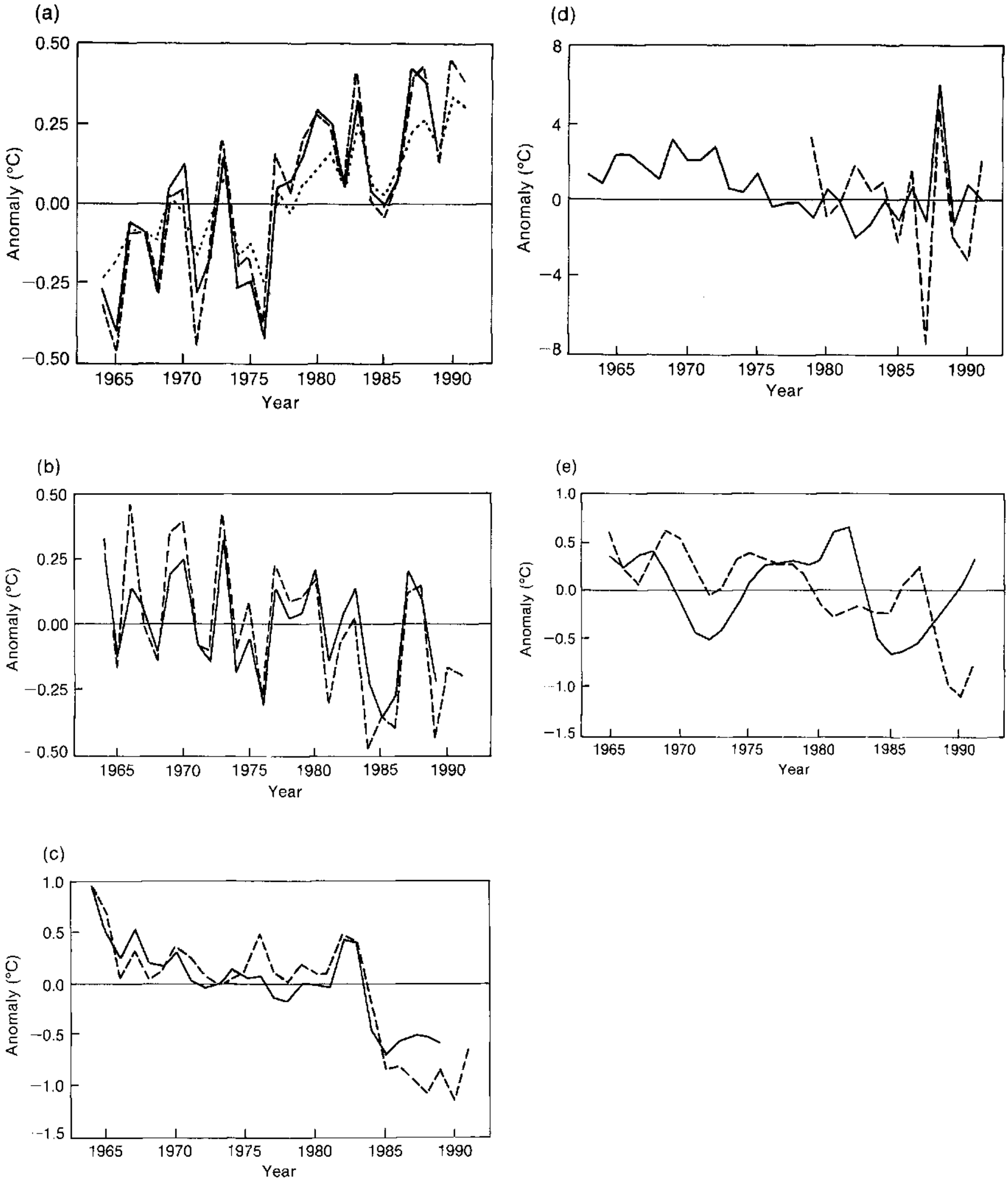


Figure C8: (a) Annual global temperature anomalies since 1964 for the surface and the 850-300 hPa layer relative to a 1964-1989 average. Surface temperatures (dotted line) are based on Figure C4. Temperatures aloft are based on the radiosonde data of Oort and Liu (1992) to 1989 (solid line) and of Angell (1988) updated to 1991 (dashed line); (b) Annual global temperature anomalies since 1964 for the 300-100 hPa layer relative to a 1964-1989 average from two analyses. Temperatures are based on the radiosonde data of Oort and Liu (1992) to 1989 (solid line) and Angell (1988) updated to 1991 (dashed line); (c) as (b) but for the 100-50 hPa layer; (d) Austral spring (Sept-Nov) temperature anomalies for the 100-50 hPa layer relative to a 1979-1991 average for the south polar cap: (i) from Oort and Liu (1992) to 1989 and from Angell thereafter for 60°-90°S (solid line); (ii) from MSU Channel 4 data for 62.5°-90°S (dashed line); (e) Smoothed annual zonal mean 30 hPa temperature anomalies relative to a 1964-1989 average for 80°N (dashed) and 20°N (solid). A low pass binomial filter with 5 terms was used to suppress variations of less than 3 years. Updated from Naujokat (1981).

of El Chichon. After this there was a sharp cooling to 1985-87. Trenberth and Olson (1989) found a lower stratospheric cooling trend in spring over the South Pole and McMurdo Sound, extending to January at 100 hPa, though there were no tropospheric trends. In fact, radiosonde data for 100-50 hPa for the south polar cap show some cooling in all seasons except autumn over the last decade or more. However, in austral spring, when the deepest ozone holes have been reported (SORG, 1991), there have been very strong interannual fluctuations of radiosonde and satellite Microwave Sounding Unit temperature (see Section C3.3.1.2) since 1985 (Figure C8d). Although, as a result, the trend in Figure C8d is not significant, the general level of lower stratospheric south polar cap temperature in spring was several degrees lower in the 1980s than the 1970s.

Low-pass filtered series of 30 hPa temperature for latitude belts of the Northern Hemisphere show weak downward trends (Figure C8e, updated from Naujokat, 1981). At many latitudes there is a suggestion of an oscillation almost in phase with the cycle of solar activity whose length over this period was quite close to 11 years, seen here in the solid curve for 20°N (see also Section C4.2.1): this should be taken into account when 30 hPa temperature trends are determined (van Loon and Labitzke, 1990; Labitzke and van Loon, 1991, 1992). Warming at 30 hPa associated with the 1982 eruption of El Chichon is especially noticeable at lower latitudes (e.g., the solid curve in Figure C8e). Data for late 1991 (not shown in Figure C8e) show another pronounced warming of up to several °C at 30 hPa. The warming, centred near 20°N and confined to regions south of 45°N, was almost certainly due to the eruption of Mt. Pinatubo in June 1991.

C3.3.1.2 Satellite microwave sounder data

S7 reported early results concerning recent tropospheric temperature trends and interannual variations from a valuable new data set derived from satellite measurements of the microwave emission of radiation to space from atmospheric oxygen (Spencer and Christy, 1990; Figure 7.17d, p221). The new technique, which uses data from the Microwave Sounding Units (MSU) on the TIROS-N series of satellites (Spencer *et al.*, 1990), measures temperature over layers of the atmosphere. Channel 2 data of the MSU is weighted towards temperature over a substantial thickness of the troposphere, but is also influenced by the stratosphere and the character of the ground surface. By using sets of Channel 2 data with different earth viewing-angles it is possible to create a new data set called Channel 2R that is mostly (not completely) weighted towards levels below 350 hPa, mainly to levels between 500 and 1000 hPa, though at the cost of a slight loss in reproducibility. In addition, Channel 4 measures lower stratospheric (mainly 30-150 hPa) temperatures. The MSU instrument is independently calibrated, so is not influenced by conventional instruments such as radiosondes, though biases, resulting from changes of satellites and equatorial crossing-times, may remain. The main advantages of the MSU system are its global coverage and a lower value of standard error at most grid points compared with radiosonde data (Spencer and Christy, 1992a,b).

A particularly important aspect of MSU data in the context of this assessment is their ability to detect temperature trends with relatively high accuracy in the layers they measure, though the MSU record is still very short (13 years). Figure C9 shows lightly smoothed monthly global Channel 4 lower stratospheric temperature anomalies relative to the complete period 1979-91. Over this short period very large, temporary but highly coherent warming effects of the volcanoes El Chichon (1982) and Mt. Pinatubo (1991) dominate the record. This makes the detection of a global trend in MSU lower stratospheric data difficult.

C3.3.1.3 Comparisons of satellite microwave, radiosonde, and surface temperature data

The correlation between 5° latitude × 5° longitude monthly time-series of surface-based temperature anomalies and of tropospheric temperature anomalies from the MSU is near zero over parts of the tropical oceans but is much higher over major land masses and oceanic areas of high variability (Trenberth *et al.*, 1992). The differences are thought to be partly due to data sampling problems in the non-MSU data sets, partly to real physical differences between surface temperatures and the mid-tropospheric temperatures, and possibly partly to uncertainties in the MSU data due to surface emissivity variations. There are also some divergences between the MSU and the radiosonde data. Consequently, the ranking of recent very warm years in the lower atmosphere and at the surface

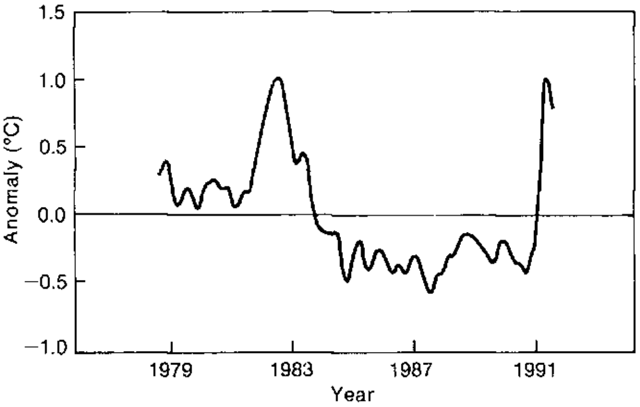


Figure C9: Smoothed monthly global MSU Channel 4 lower stratospheric temperature anomalies, for 1979 to 1991 relative to a 1979-1991 average. A binomial filter with 5 terms was used.

depends on which record is used, what level is being referred to and how much uncertainty is attached to each value.

Figure C10 compares annual global temperature anomalies for 1979-91 for the mid-troposphere from MSU Channel 2R, with values for the 850-300 hPa layer from radiosondes using Oort and Liu to 1989 and then Angell to 1991, and for the surface using the data in Figure C4c. Table C3 presents the intercorrelations (r) for MSU 2R (suffix m), radiosonde (suffix sd) and surface data (suffix sf), their linear trends (τ) in °C per decade, and the standard deviations, σ, of the annual values. Note, however, that the linear trends for 1979-1991 are not fully representative of those for the longer term.

At this stage we merely note that the calculated linear trends for 1979-1991 are different, though all but one are positive. The correlations between the surface and the MSU data are lower than those with the radiosonde data. The correlations may be reduced by the fact that the MSU data samples regions not sampled or poorly sampled by the radiosonde and surface data, especially in the Southern Hemisphere, but further investigation is needed to clarify this. Much, though not all, of the difference in the trends between the MSU and the other data comes from disagreements in the annual anomalies for 1979, 1980 and 1981. It is clear that the data sets have some different characteristics. The short period of overlap (1979-1991), differences in the variables being measured and doubts about the year-to-year consistency of the data sets, prevent reliable assessment of the differences in trends. Reliable assessment of future trends in MSU data will require the compatibility of new MSU instrumentation with that used at present. The continued availability of all three data sets is very desirable to help reduce the problems noted above.

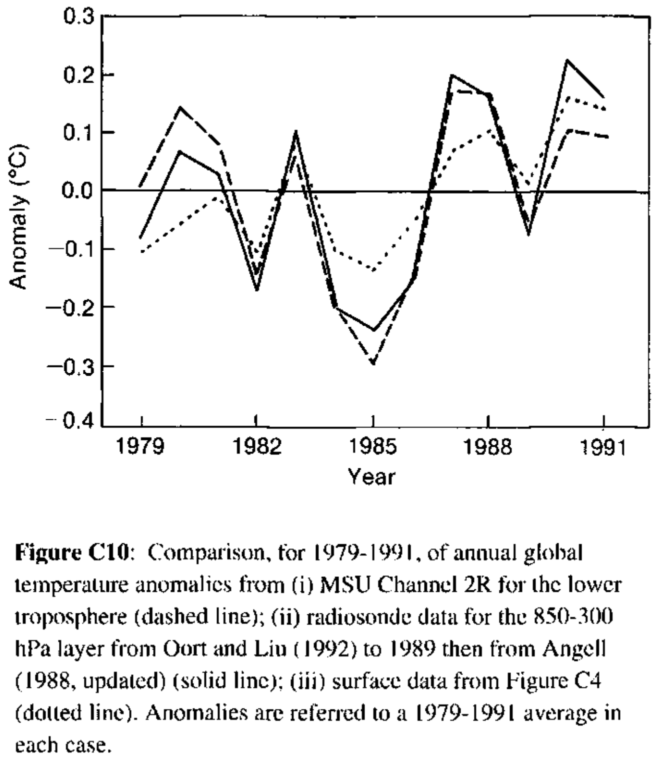


Figure C10: Comparison, for 1979-1991, of annual global temperature anomalies from (i) MSU Channel 2R for the lower troposphere (dashed line); (ii) radiosonde data for the 850-300 hPa layer from Oort and Liu (1992) to 1989 then from Angell (1988, updated) (solid line); (iii) surface data from Figure C4 (dotted line). Anomalies are referred to a 1979-1991 average in each case.

C3.3.2 Atmospheric Moisture

For previous discussions, refer to S7, p222 and S8, p251; in the current volume Section B3.2 gives a more detailed discussion of the likely role of water vapour during a greenhouse gas-induced warming. Water vapour is the greenhouse gas in greatest abundance and is responsible for the largest single contribution to greenhouse warming of any of the constituents of the atmosphere in the current climate.

The sensitivity of the surface temperature to height-dependent moisture changes was examined by Shine and Sinha (1991) who point out the importance of changes in water vapour content **throughout** the depth of the troposphere. They show that changes in much of the mid-troposphere are important as they tend to be large due to the relatively great amounts of water vapour there. However, despite the small absolute amount of water vapour in the upper troposphere and stratosphere, they show that changes at this level can also have a significant effect on the radiation forcing of climate. Furthermore, an increase in moisture in the stratosphere could lead to the creation of further polar stratospheric clouds which have an important effect on ozone depletion in the presence of chlorine derived from chlorofluorocarbons. Stratospheric water vapour is also important in the conversion of SO_2 to sulphuric acid droplets which can cool surface climate after a sulphur-rich volcanic eruption. Furthermore,

***Table C3:** Annual MSU 2R, radiosonde 850-300hPa and surface temperature anomalies, 1979-1991: intercorrelations, trends and standard deviations*

	$r_{sd, m}$	$r_{sd, sf}$	$r_{m, sf}$	τ_m	τ_{sd}	τ_{sf}	σ_m	σ_{sd}	σ_{sf}
NH	0.96	0.91	0.84	0.12	0.21	0.23	0.18	0.18	0.15
SH	0.86	0.71	0.42	-0.02	0.13	0.14	0.13	0.14	0.08
Globe	0.93	0.90	0.74	0.06	0.17	0.18	0.15	0.16	0.10

oxidation of methane generates stratospheric water vapour; so increases in methane, from whatever causes, can lead to an increase in stratospheric moisture.

In an examination of strategies for detecting greenhouse gas signals, Barnett *et al.* (1991) find tropospheric moisture to be one of the most effective variables to monitor. However, monitoring moisture presents many difficulties and, since its variation is physically linked to changes of temperature, it does not provide an independent measure of greenhouse forcing. The residence time of water vapour in the atmosphere is short, about 10 days, so it is not well mixed. If the water vapour in the air were all condensed, the average depth of the condensate (the precipitable water, PW), would be about 2.5cm. Above the polar regions the mean PW is about 0.5cm, and above the equatorial regions it averages about 5cm. Half the moisture in the atmosphere lies between sea level and 850 hPa and less than 10% resides above the 500 hPa level. Therefore, observations at many places and levels are required to adequately study changes in water vapour likely to be climatically important.

Measurement problems make trends of water vapour difficult to determine. Most of the existing knowledge about tropospheric water vapour comes from routine radiosonde observations. Unfortunately, radiosonde data have been affected by changes in humidity sensors and reporting procedures, and some sensors and retrieval algorithms do not provide useful results in the low temperatures and very dry conditions of the upper troposphere and lower stratosphere. This makes it difficult to separate climatic changes from changes in the measurement programme (Elliott and Gaffen, 1991). Nevertheless, with careful attention to these problems some deductions can be made.

Recently Elliott *et al.* (1991) have documented a moisture increase in the lower troposphere over the equatorial Pacific from 1973-1986; additionally Gaffen *et al.* (1991), using more stations and an analysis of individual moisture patterns, have found an increase in moisture in the tropics. At 850 hPa, this study found an increase of specific humidity of around 10% between 1973 and 1986, though this value is very uncertain as the scatter in the data is comparable to the trend and most of the change occurred during the short interval 1977-1980. The study also detected a signal of the ENSO phenomenon (S7, p226) in the humidity data.

Thus, there is limited observational evidence suggesting an increase in lower tropospheric moisture content in tropical regions over the last two decades. These results support the apparent increase of evaporation from the oceans (Section C3.2.3). A much more comprehensive atmospheric moisture monitoring system is needed, such as may be provided by the Global Energy and Water Cycle Experiment (GEWEX) (WMO, 1991).

C3.4 Variations and Changes in the Cryosphere

This section should be read in conjunction with Section C2, where recent work on oxygen isotopes in Antarctic land-ice is discussed, and with S7, Section 7.8. Section 9.4.3 of S9 (Warrick and Oerlemans, 1990) and the brief review by Haeberli (1990) should be consulted on permafrost and other cryospheric features.

C3.4.1 Snow Cover

Snow extent is very variable; it is affected by temperature through atmospheric circulation variations which also influence the quantities of solid and liquid precipitation.

The Northern Hemisphere snow extent anomaly time-series shown in Figure 7.19 of S7 (p224) has recently been revised. A change in analysis technique had resulted in snow extents analysed prior to 1981 being slightly too large relative to later values (Robinson *et al.*, 1991). A revised series from 1973 to 1991 is given in Figure C11. This still shows a modest decrease in snow cover since the 1970s but with a reduced magnitude: mean values over 3 years dropped by just over 2 million km^2 from the mid-1970s to the end of the 1980s, about 8% of the total area. In Figure 7.19 of S7, a decline of about 3 million km^2 was indicated. The new snow extent values have good support from a parallel plot of extratropical Northern Hemispheric land air temperature (Figure C11). The correlation between the monthly (September to May only) anomalies of snow cover and temperature is -0.41, but between unsmoothed annual (average of Sept-May) anomalies it is -0.76 because presumably influences other than those of temperature partly cancel. Snow extent has been especially low in spring since 1987, most notably in spring 1990. However, the snow extent record is still much too short to distinguish a possible greenhouse signal from natural variability.

C3.4.2 Mountain Glaciers

A major result of S7 (see Executive Summary) was the conclusive evidence for a worldwide recession of mountain glaciers over the last century or more. This is among the clearest and best evidence for a change in energy balance at the Earth's surface since the end of the last century. It provides sufficient support to the various independent but far from perfect records of global temperature to show that global warming has indeed occurred over the last century (Haeberli, 1990). On a regional scale, however, the influence of climate can be much more complex, especially on decadal and lesser time-scales where precipitation fluctuations may be important or even dominant.

Direct information on mass balance is available from a small number of glaciers in the European Alps where these observations started during the late nineteenth century. The average annual loss of specific mass (mass per unit area) amounts to between 0.2 and 0.6 m water equivalent

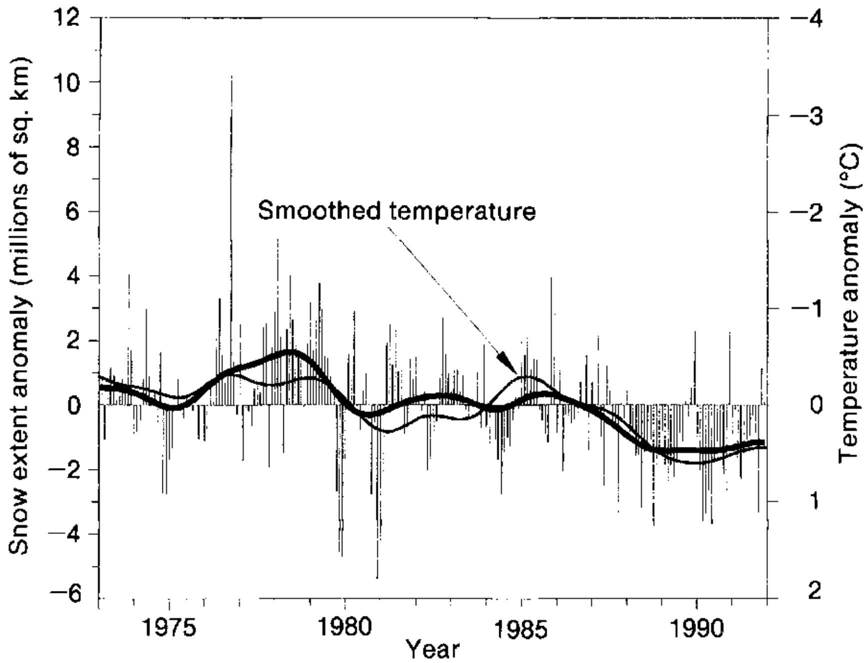


Figure C11: Northern Hemisphere snow extent anomalies relative to 1973-1991 (from NOAA, USA) (vertical bars and heavy line) and Jones (1988, updated) land air temperature anomalies relative to 1951-80 north of 30°N (thin line). Smooth lines generated from a 39-point binomial filter applied to the monthly data. Note the inverted temperature scale.

(Patzelt and Aellen, 1990). Regularly monitored glaciers, however, account for less than 1% of the total number of glaciers worldwide. Much more numerous are measurements of glacier length reductions which can be converted into mass balance values using a combination of continuity analyses and data on initial glacier length. They confirm the representativeness of the small number of direct long-term mass balance measurements (Haeberli, 1990). Aerial and ground surveys indicate that most observed mountain glaciers are distinctly smaller than a century ago (Haeberli and Müller, 1988; World Glacier Monitoring Service, 1991; Williams and Ferrigno, 1988-1991).

Some of the techniques used to estimate the overall glacier mass decrease in the Alps since the middle of the nineteenth century are controversial. Recently, Haeberli (1990) has estimated a 50% decrease in mass. Though this is subject to marked uncertainty, a relatively large decrease is likely. This drastic change is the consequence of an upward shift in equilibrium line altitude by only 100m or less. Twentieth-century melt rates of Alpine glaciers are an order of magnitude greater than average melt rates at the end of the last ice age (20,000 to 10,000 years ago).

Statistical analysis of spatial and temporal variations in mass balance series from glaciers on various continents (Reynaud *et al.*, 1984) indicates that the historical behaviour in the Alps may be representative of glaciers in general, confirming the great sensitivity of glacier volume to climate variations. A global-mean reduction in volume may be estimated from average ice volume data in S9 (Table 9.3) and the estimated sea level rise contribution from mountain glaciers and small ice-caps (Meier, 1984). This gives a reduction of 13±9% in volume over the last century. Despite this, the retreat of Alpine glaciers has not been uniform on decadal time-scales, as mentioned in S7, p225, with a marked net advance in the period 1965-1980, coinciding with colder average temperatures over most of the North Atlantic and over western Europe (see S7, graph in Fig 7.12a).

In contrast to the above, high and middle latitude coastal glaciers may grow under warmer and wetter conditions. Mayo and March (1990) report that the Wolverine glacier in the maritime region of southern Alaska near 60°N had generally positive mass balances after 1976 as a result of increased winter precipitation which fell as snow, despite warmer winters, because temperatures remained well below freezing. This change is likely to be associated with the rather striking increase in winter half-year cyclonic activity in the Gulf of Alaska since 1976 discussed in S7, p229. In addition, Fitzharris *et al.* (1992) note that the terminus of the Franz Josef glacier on the west coast of New Zealand has advanced in the 1980s, as have other alpine glaciers in New Zealand, despite the fact that the 1980s were locally one of the warmest decades in the record. Atmospheric circulation changes partly associated with ENSO appear to be involved.

An overall shrinking trend in the glaciers of the Northern Hemisphere has continued into the late 1980s (World Glacier Monitoring Service, 1991). Recent data

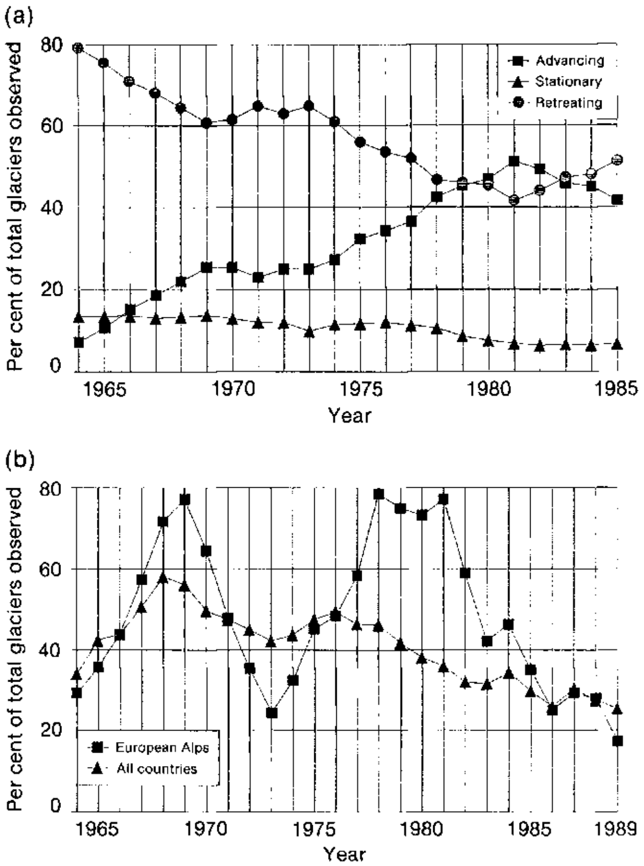


Figure C12: (a) Percentages of observed glacier fronts advancing, stationary and retreating. Data from all available countries; number of glaciers ranges from 271 in 1959/60 to 486 in 1984/5. Values are 5-year moving averages from 1959/60-1963/64 to 1980/81-1984/85. Data from Haeberli and Müller (1988) and Wood (1988); (b) Percentages of observed glaciers having a positive mass balance: (i) all countries (triangles); (ii) about 10 European Alpine glaciers (rectangles). Values are 5-year moving averages from 1959/60-1963/64 (53 glaciers from all countries) to 1984/85-1988/1989 (71 glaciers from all countries). Data from Haeberli and Müller (1988), Wood (1988), World Glacier Monitoring Service (1991), U.S. Geological Survey and Canadian National Hydrology Research Institute.

suggest that mountain glaciers are, as a group, shifting back to a regime dominated by shrinkage and recession, after a period of relative growth and minor re-advance during the 1960s and 1970s (Figures C12a and b). However, this temporary re-advance has not affected the larger glaciers. In further support of this conclusion two detailed regional studies are mentioned. In a study of trends in the length of 242 glaciers in northwest China from the 1950s to 1980s, Shi (1989) shows that 42% were retreating, 29% showed little change and only 29% were advancing. The overall glacier retreat is thought to result from both a warming and a drying trend in this area. In the Southern Hemisphere, Aniya and Naruse (1991) reported that in the northern Patagonian icefield, 20 of the 22 major outlet glaciers were retreating and only one was advancing. A general review of glacier and other cryospheric trends is given in Barry (1991).

More extensive glacier monitoring and comparative analyses of climatic data are needed to add to these results, as glacier fluctuations are potentially important indicators of regional and global climatic change.

C3.4.3 Polar Ice Caps

Morgan *et al.* (1991) derived time-series of the net rate of snow accumulation since 1806 from four cores separated by up to 700km in a limited area in East Antarctica within 300km of the coast. The four cores yielded fairly similar results. There has been a significant increase in accumulation rate after a minimum around 1960 and the most recent values are the highest observed in the record. Morgan *et al.* (1991) attribute the recent imbalance to increased cyclonic activity around Antarctica leading to higher snowfall. Increased temperatures usually accompany increased snowfall, resulting in positive correlations between temperature and accumulation in Antarctica (Jones *et al.*, 1992). However, it is unclear how widespread this increase in accumulation has been, so it is too soon to revise the estimates of the contribution that Antarctic ice accumulation may make to sea level reduction that were summarized in S9.

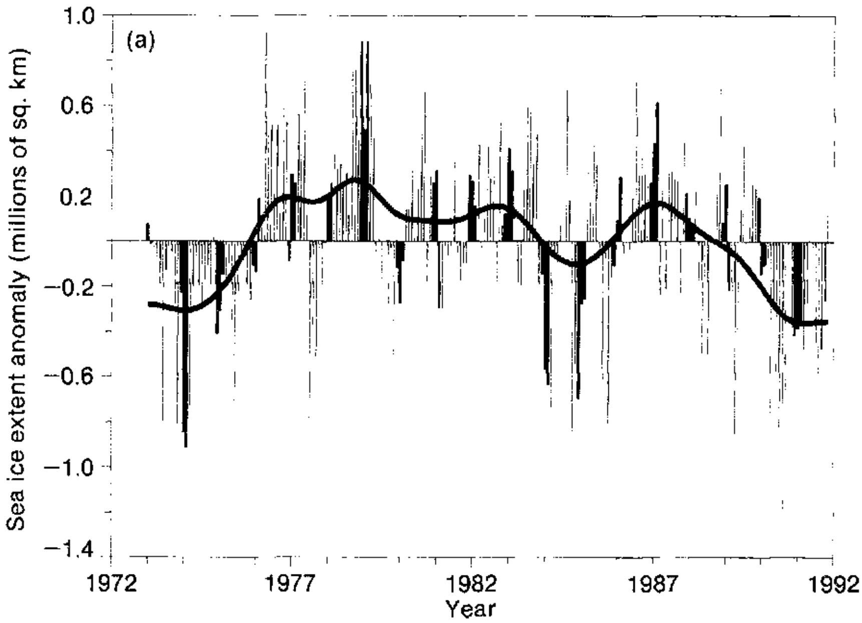
The Wordie ice shelf, on the western side of the Antarctic Peninsula, has shrunk markedly from about 2000km^2 in 1966 to about 700km^2 in 1989 (Doake and Vaughan, 1991). This is apparently related to a strong regional warming trend. However, the larger ice shelves, such as the Ross and Filchner-Ronne, which help to stabilize the West Antarctic ice sheet, would only be threatened by substantially greater warming (Zwally, 1991).

For evidence from satellites concerning a recent thickening of the Greenland ice sheet, the reader is referred to S9, Section 9.4.4.

C3.4.4 Sea-Ice

No simple relationships have been established between sea-ice extent and temperature, either for the Antarctic (Raper *et al.*, 1984) or for the Northern Hemisphere (Kelly *et al.*, 1987).

A re-analysis of satellite passive microwave data obtained by Nimbus 7 (Gloersen and Campbell, 1991) shows a statistically significant 2.1±0.9% decline in the extent of Arctic sea-ice (including enclosed open water areas) between 1978 and 1987 and an accompanying non-significant 3.5±2.0% reduction in the open-water areas, i.e., polynyas and leads, within the ice field. Figure 7.20a in S7 also indicates a decline of about 0.2×10^6km^2 (2%) in the extent of Arctic sea-ice between 1978 and 1987, but there is no decline over the whole period. So the Gloersen and Campbell result, while supported, seems not to be



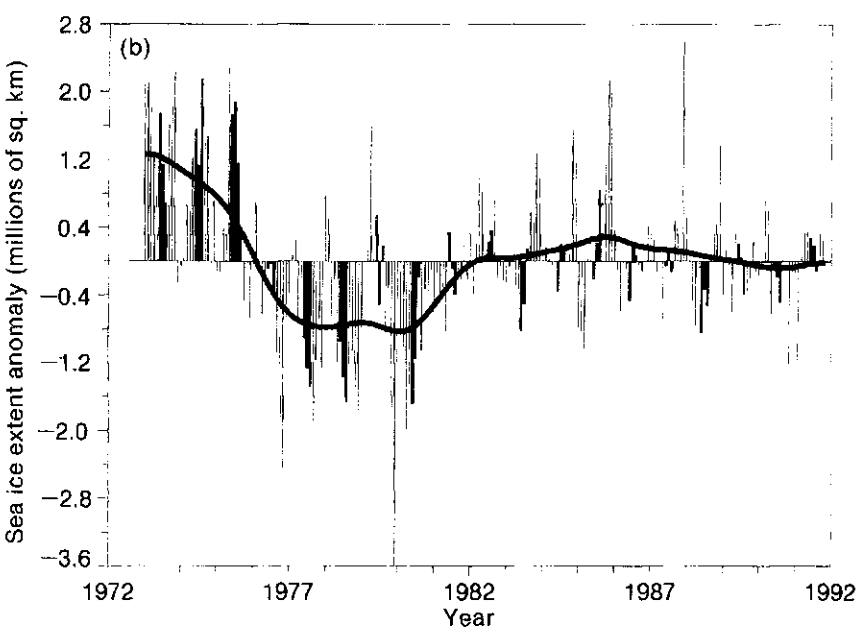


Figure C13: (a) Northern Hemisphere, (b) Southern Hemisphere sea-ice extent anomalies relative to 1973-1991. Data from NOAA (USA). Smooth lines generated from a 39-point binomial filter applied to the monthly anomalies. Heavy bars represent DJF in the NH or JJA in the SH.

representative of the whole period and it cannot therefore be interpreted as a trend. Over the same time interval the above authors found no significant trends in Antarctic sea-ice. Figures C13a and b update the hemispheric sea-ice extent variations shown in Figures 7.20a and b of S7 to the end of 1991. As suggested in S7, no systematic trend toward more or less sea-ice is apparent from the short records compiled to date. In 1990 and 1991, sea-ice extent remained less than the 18-year mean in the Arctic and near the mean in the Antarctic.

It now seems even less likely that the postulated thinning of Arctic sea-ice addressed in S7, based on the submarine observations of Wadhams (1990) north of Greenland, reflects a basin-wide phenomenon. Three issues of concern are (1) the use of data from only 2 cruises in different seasons (May 1987 and October 1976); (2) the year-to-year variability in ice motion in the Beaufort Gyre and Transpolar Drift Stream that may affect the ice regime north of Greenland; (3) the absence of a reliable baseline climatology because the numerous submarine cruises have travelled different routes in different seasons through sectors with widely differing ice conditions (McLaren *et al.*, 1990).

C3.5 Variations and Changes in Atmospheric Circulation

S7, pp225-229, identified in particular recent increases in the intensity of the winter atmospheric circulation over the extratropical Pacific and Atlantic (Figures 7.22 and 7.23): see Trenberth (1990) for a fuller discussion. These findings are reflected in an analysis of the climate of the 1980s by Halpert and Ropelewski (1991) and in analyses by Flohn *et al.* (1992). However, beyond these results, it is difficult to identify new research on atmospheric circulation changes that does not depend critically on how the analyses were done and on the choice of data. It is recognized, though, that studies of atmospheric circulation changes are a key topic for future research as such changes are likely to be an important component of future regional climatic change.

C4 Detection and Attribution of Climatic Change

C4.1 The Greenhouse Effect

"Fingerprint" detection of the influence of an enhanced greenhouse effect, by comparing the patterns of climate change predicted by models with historical observations, is fully discussed in S8. Progress is very difficult (a) because multiple runs of coupled ocean-atmosphere models are needed, requiring very large computer resources; (b) these models may still not be adequate, particularly because of the "flux correction problem" (see Section B2.2); (c) adequate data series are very few and short; and (d) the methodology to implement the technique has not fully matured. In addition, the climate system can respond to many forcings and it remains to be proved that the greenhouse signal is sufficiently distinguishable from other signals to be detected except as a gross increase in tropospheric temperature that is so large that other explanations are not likely (see S8). Because of these difficulties, no definitive paper on detection has appeared since the 1990 IPCC Scientific Assessment. The reader is referred to Karoly *et al.* (1992) for a recent discussion of some of the problems and possible ways forward.

C4.2 Other Factors

C4.2.1 Solar Influences

Possible changes in solar irradiance and their climatic effects were discussed in S2, while Section A2.7 of this Assessment discusses new physically-based evidence about variations in the luminosity of stars like the Sun on century time-scales. Reid (1991) has re-examined the case for solar forcing of global surface temperature in phase with an approximately 80-year ("Gleissberg") modulation of the amplitude of the near 11-year cycle in sunspot numbers. He first formed a relationship between this amplitude and the solar constant using a limited series of measurements since the 1960s. He then used a simple model to predict the global SST from the variation of solar forcing reconstructed in this way back to 1660, and found that the simulated global SST and a version of the observed global SST were well correlated since 1860. Due to a lack of sufficiently long time-series of satellite measurements of solar irradiance, Reid's conclusions rely considerably on rocket- and balloon-borne measurements of total solar irradiance made in the late 1960s; these are of uncertain accuracy and representativeness. His conclusions also depend on the reliability of the shape of the observed global temperature series, especially prior to 1900 (Reid used an early version of the Bottomley *et al.* (1990) SST data). Strong auto-correlations in both the solar and temperature data also mean that very few degrees of freedom are being compared in each data set.

A new approach by Friis-Christensen and Lassen (1991) (FCL) uses the **length** of the sunspot cycle which is known to be statistically related to solar activity. They hypothesize that shorter cycles are directly related to higher solar magnetic activity which in turn they assume corresponds to a higher total output of solar radiation, though no firm physical basis has been established for this relationship. The length of the solar cycle varies between 7 and 17 years. After smoothing the cycle length data, they find a correlation of -0.95 between cycle length and Northern Hemisphere land surface air temperature since 1860 when averages over corresponding solar cycles of these data sets are compared. FCL do not compare their solar results with a global surface temperature series because they prefer to use temperatures over land which they assume are more likely to be accurately determined than those over the sea. They also find that shorter cycles (supposedly higher solar radiation) correspond with less Icelandic sea-ice since 1740.

In the past, many authors have claimed to largely explain, in a statistical way, the hemispheric or global temperature record in terms of a single forcing factor, but different authors have chosen different factors. A full discussion of such work and why different authors can come to radically different conclusions appears in Wigley *et al.* (1986) and in S2. Recent examples are: (1) After allowing for the influence of ENSO and a (different) index of solar variability, Wu *et al.* (1990) claim that the variations of global and regional night marine air temperature, and to a lesser extent SST, over the last century published by Bottomley *et al.* (1990) can be mainly explained by an atmospheric turbidity index. This index is claimed to relate mainly to the variations in stratospheric dust due to volcanic activity, being based on measurements made at 3100m altitude, but it might, nevertheless, include some influence of tropospheric aerosols as well (Section C4.2.4). (2) Schönwiese and Runge (1991) and Schönwiese and Stahler (1991) explain regional climate changes on the same time-scale in great detail largely in terms of CO_2 forcing, though volcanic, solar and ENSO influences are also included. These and other exercises in curve fitting can demonstrate statistical relationships, but cannot prove physical connections.

A full discussion of the relation between the historical temperature record and different forcing factors requires that greenhouse forcing be included (Kelly and Wigley, 1990; Hansen and Lacis, 1990). Although we do not know what the *response* of the recent past climate to greenhouse forcing has been, we *do* know the approximate *magnitude* ($2Wm^{-2}$ at the top of the troposphere) and *rate of increase* of the greenhouse-gas *forcing* over the last century (Figure 2.2 of S2, p55). Furthermore, empirical studies of relationships between smoothed forcing factors and the statistically non-stationary historical temperature record cannot, alone, resolve the relative contributions of the different forcing factors. The main problem lies in the similarity of the trends of the forcing factors and the small number of degrees of statistical freedom in the data, which often show long-term persistence. In addition, rigorous statistical tools do not exist to show whether relationships between statistically non-stationary data of this kind are truly statistically significant, even though the correlations found by each author between their chosen forcing factor and the temperature record are invariably quite high (Zwiers, personal communication). Thus a **physical** model that includes both the hypothesized forcing and the enhanced greenhouse forcing must be used to make further progress.

C4.2.2 Bi-decadal Temperature Variations

A renewed controversy has developed about the existence of globally significant temperature variations on typically 18-22 year time-scales. These variations are often related to the solar 22-year magnetic cycle (Newell *et al.*, 1989), or sometimes to the 18-19 year lunar orbital cycles (Currie and O'Brien, 1990) which can, in principle, have small tidal effects on the oceans. Ghil and Vautard (1991) have claimed to find a bi-decadal oscillation in global surface air temperature using a novel form of analysis (singular spectrum analysis), mirroring similar findings by Newell *et al.* (1989) in global night marine air temperatures based on more conventional techniques. However, Elsner and Tsonis (1991b) show that the bi-decadal variation which appears in Ghil and Vautard's analysis depends critically on the inclusion of less reliable late nineteenth century data. In view of the possible influence of this variation on our perception of recent trends, further research is warranted.

C4.2.3 "Abrupt" Climatic Changes

Features of many irregular climatic time-series are apparently sudden, usually not very large, changes in average value; or sudden changes of trend, such as are seen in the global and hemispheric temperature series (Figures C2, C3 and C4). Statistical tests exist to suggest whether the mean has changed significantly (Demarée and Nicolis, 1990) or whether a significant change in trend has occurred (Solow, 1987). Usually, investigators test one or other of these hypotheses, but not both, so the conclusion drawn can depend on the hypothesis that is chosen to be tested and whether tests are chosen in advance of the analysis of the data or subsequently (Karl, 1988). Nevertheless, some of these changes may have a real physical cause and be of obvious importance, such as the rather sudden change in the mean winter half year pressure around 1976 in the extratropical North Pacific shown in Figure 7.23 of S7, p 229 and discussed by Trenberth (1990).

Lin and Zhou (1990) ascribe a climatic "jump" to a series if the difference between the average values for two successive periods is statistically significant according to a t-test, and the length of the transition time between the periods is "much less" than their duration. However, they appear to have pre-selected the dates of the jumps, violating an assumption of the t-test (see Karl, 1988). Also, an analysis is needed of how often such behaviour would occur in truly random series or in stationary series exhibiting persistence. Inevitably, some "jumps" so defined will occur and will be statistical artefacts. The annual Sahel rainfall series illustrates some of the problems (see Figure 7.16b of S7). Demarée and Nicolis (1990) suggest that a statistically significant sudden reduction in average value occurred in 1967-8, whereas the studies of Folland *et al.* (1986) and Rowell *et al.* (1992) indicate that the change of rainfall between the 1950s and 1970s was associated with **a relatively steady, if rapid,** change in interhemispheric SST patterns, a link identified from empirical and modelling studies. It is important for physical understanding of the causes of the Sahel rainfall changes that these contrasting interpretations be reconciled. Many other examples of such "fast" changes exist in regional and local climate records (e.g., Karl and Riebsame, 1984), though few have been subjected to rigorous analysis.

Statistical tests applied to rapid climate changes have a useful role. However, the underlying hypotheses should accord as far as possible with the physical character of the causative processes. Sometimes, for example, apparently abrupt changes between two climatic mean states (e.g., Demarée, 1990) may result from simultaneous processes operating on different time-scales. Climate models should be used to help to uncover these processes.

C4.2.4 Aerosols

C4.2.4.1 Man-made aerosols

A detailed discussion of man-made aerosols, their precursors, and their forcing effects on climate is in Section A2.6. Here we limit discussion to the possible effects of aerosols on the temperature record. The atmospheric concentration of aerosols, particularly those derived from man-made emissions of SO_2, has increased significantly this century in many parts of the Northern Hemisphere, and sulphate concentrations in industrialized areas of eastern Europe and eastern North America are now 10-15 times larger than the expected natural concentration of sulphate (see Section A). The bulk of the increase of SO_2 emissions began in the early 1950s. As stated in Section A, man-made, SO_2-derived aerosols are important because they may have acted to retard the expected warming from the build-up of greenhouse gases and to produce a slower rate of warming in the Northern Hemisphere (i.e., a relative cooling) compared with the Southern Hemisphere. The approximately $1Wm^{-2}$ negative forcing confined to the Northern Hemisphere discussed in Section A2.6.1.2 would offset about 50% of the enhanced greenhouse forcing of about $2Wm^{-2}$ over the past 100 years.

Figures C4a and b show that from about 1910 until the 1950s the Northern Hemisphere surface warmed with respect to that of the Southern Hemisphere. This differential warming, though consistent with some model predictions of more warming in the Northern Hemisphere compared with the Southern Hemisphere as greenhouse gases are added to the atmosphere, is more likely to have been of natural rather than man-made origin, in view of the small increase of these gases over that period. From the 1950s until about 1980, however, the surface of the Southern Hemisphere warmed relative to that of the Northern Hemisphere by nearly 0.3°C (Table C1). The timing of the reversal of relative warming might suggest that sulphate aerosols have been a contributory cause, but renewed warming of the Northern relative to the Southern Hemisphere in the last few years (Figure C4) shows how uncertain such conclusions can be. There is, however, evidence of a reduction in sulphate aerosol emissions from Western Europe since 1980 (Smith, 1991) which could have contributed to renewed warming in the Northern Hemisphere. These results do not prove the hypothesis of a significant aerosol cooling effect on the observed climate because the likely signal is still only of a magnitude similar to the natural variability (Wigley, 1989; Wigley *et al.*, 1992). Many other variables, such as cloudiness changes and ocean circulation variations involving the North Atlantic (S7, Section 7.7), may lead to natural differences between hemispheric temperature trends.

C4.2.4.2 Volcanic aerosols

The major eruption of the Philippines volcano Mt. Pinatubo in June 1991 may be sufficiently great in its climatic effects to allow better physical theories of the influence of volcanic eruptions on climate to be developed. Section A2.6.2 discusses this further. The August 1991 eruption of the Chilean volcano Cerro Hudson was at least 10 times smaller than that of Pinatubo in terms of the amount of SO_2 emitted into the stratosphere, but was still about twice as large as that of Mt. St Helens in 1980 (Doiron *et al.*, 1992). Mt. Pinatubo may have placed nearly 3 times as much material into the stratosphere as did the strong El Chichon eruption of 1982 (Bluth *et al.*, 1992). However, Stowe *et al.* (1992), using a different technique, have estimated that the Pinatubo eruption may have placed a little less than twice as much material there. It is provisionally estimated that this sulphur-rich eruption, which is the type currently thought to have the maximum climatic effects, will temporarily reduce global mean surface temperature by 0.3°-0.5°C over the next year or so (Stowe *et al.*, 1992). The upper end of this estimate is indicated by model simulations carried out by Hansen *et al.* (1992) of the possible effect of Pinatubo stratospheric aerosols on global land temperature, assuming that the aerosols contain twice as much sulphur as did those of El Chichon. If this cooling happens, the consequences of the Pinatubo eruption, with a small extra contribution from Cerro Hudson, could dominate the global surface temperature record in 1992 or a little beyond. In response to heating of the aerosols, globally averaged lower stratospheric temperatures measured by MSU Channel 4 rose by about 1.3°C between June and October 1991, but then began to decline (Figure C9). MSU mid-tropospheric temperatures fell by over 0.5°C between June 1991 and December 1991, though such decreases are common in the record (Spencer and Christy, 1990).

C4.2.5 Changes in Land Surface Characteristics

Balling (1991) has pointed out that changes in the amount of vegetation due to man's activities can change temperatures regionally. Thus, removal of vegetation, perhaps leading eventually to desertification, tends to raise near-surface air temperatures, at least in warmer climates, as more of the incoming solar radiation is used to heat the ground and less is used to provide energy for the transpiration of plants and trees. Such tendencies will be offset by any accompanying increase in surface albedo, and the net effect may depend on the character of the initial vegetation as indicated by studies in Africa (Wendler and Eaton, 1983). Balling contends that, if a fraction of the observed global warming can be attributed to man-made land-use changes, then less can be attributed to the enhanced greenhouse effect. Conversely, such effects need to be balanced against the local surface cooling that is likely in areas where irrigation, new crop growth and new lake surfaces have been developed in recent decades.

C4.2.6. Deep Ocean Heat Storage

A possible cause of the Northern Hemisphere cooling trend between the 1940s and the 1960s relates to a change in the oceanic circulation in the North Atlantic which temporarily took more heat from the atmosphere into the deep ocean (Wigley and Raper, 1987). S7, p222-223 and Figure 7.18, noted that there is good evidence for warming below about 600m in the North Atlantic between 1957 and 1981 and cooling above this level, especially near the surface. Watts and Morantine (1991) note the evidence for warming in the deeper layers of the North Atlantic and calculate that the heat storage involved would approximately cancel the heat input at the surface due to the simultaneous increase in greenhouse gases, confirming the earlier results of Wigley and Raper (1987).

Recent measurements through the full depth of the ocean in the South-West Pacific at 28°S and 43°S (Bindoff and Church, 1992) show a small warming over much of the water column between 1967 and 1989 which is significantly larger than the seasonal signal or measurement uncertainties. However, the record is too short and intermittent at present to distinguish a warming trend from interdecadal variability.

C5 Concluding Remarks

The main conclusions of S7 concerning the reality, character and magnitude of global and hemispheric warming over the last century remain unaffected by recent evidence. The most challenging result of recent research is probably the increasingly widespread evidence, though not yet conclusive in a globally-averaged sense, of a marked decrease in the diurnal range of temperature over land largely produced by rising minimum temperatures (Section C3.1.5). Is this the result, perhaps partly through increases in cloudiness, of an important anthropogenic effect related to increasing tropospheric aerosols and are increases in greenhouse gases making a contribution? Wider investigations of the response of the diurnal temperature cycle in general circulation models to these effects, differentiated into clear-sky and cloudy conditions, would be very desirable.

In view of the long-standing arguments over the possible role of solar variability in climate change, which have emerged again here, it is desirable that more progress be made in modelling solar dynamics so that likely variations in solar luminosity on time-scales of the solar cycle to millennia can be better judged.

Detecting climate change and attributing it to natural variability, greenhouse forcing or other factors will require a much more **interactive and coordinated** use of data sets and models than has hitherto generally been the case. The historical data base needs much improvement as it has serious problems of heterogeneity (e.g., Parker, 1990), inaccessibility and poor coverage (Folland *et al.*, 1990a; Trenberth *et al.*, 1991). Efforts to tackle some of these problems are now increasing (e.g., Frich *et al.*, 1991). Differences between the satellite MSU data and the radiosonde and surface temperature data need detailed investigation while data describing atmospheric circulation variations, known to contain serious inhomogeneities, needs much more scrutiny. Recent *in situ* and remotely-sensed data need to be optimally blended and made consistent with historical records; this may allow a nearly full global coverage of several data sets for the last decade or more. Heterogeneities in operational analyses of the atmosphere reveal the urgent need for their "re-analysis" over as long a period as possible using a state-of-the-art four-dimensional data assimilation. This will allow the mechanisms of climate change and variability to be much better studied and some of the recent global data sets to be improved.

In the future, remote sensing data must be much more extensively used in climate change studies. However, to achieve the potential of satellite data for studying climate change, the development of methods to ensure homogeneity of processed remote sensing data with historic data will be essential. The satellites, to be truly useful, must provide continual coverage and efforts must be made to sustain their calibration over very long periods. In this context, the proposals for a Global Climate Observing System (GCOS) are highly relevant. In the meantime, surface data from developing countries and from marine archives need to be rescued, quality-controlled and added to existing analyses. Finally, documentation of changing instrumentation, processing schemes, and observing practices must be much better systematized so that artificially induced trends in all climatic data can be more adequately quantified (Karl *et al.*, 1992).

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